2024 White Paper

Wind Turbine Main Bearing Reliability Analysis, Operations, and Maintenance Considerations

TABLE OF CONTENTS

ABSTRACT

Wind turbine main bearing failure is one of the primary reasons for increases in operations and maintenance (O&M) costs and turbine downtime, especially on some of the larger land-based wind turbines (2X–6X megawatt fleet). Turbine original equipment manufacturers (OEMs) may purchase main bearings from a supplier with limited visibility on design (incomplete specifications) and manufacturing quality (lack of traceability). Bearing parts (inner race, outer race, cage, and rollers) can be manufactured at various locations around the world, leading to more uncertainty regarding part quality and life. It is important for owners/operators to know the impact of these design and manufacturing issues on the turbine operational costs. In addition to the design of these bearings, the turbine model, drivetrain assembly (blades, pitch, hub, main shaft, and gearbox), lubrication system, grease properties, and operating conditions have a significant impact on the main bearing life. This paper addresses these issues and includes land-based main bearing reliability analysis, failure mechanisms, damage modes, life-impacting factors, maintenance best practices, and mitigation strategies to extend the life of main bearings and reduce O&M costs.

TECHNICAL AND BUSINESS CHALLENGES

Cumulative land-based and offshore wind turbine global capacity is expected to reach 1,130 gigawatts (GW) by the end of 2024 [1]. To support further wind growth to meet net-zero and decarbonization goals in the coming decades, there have been growing demands for reductions in capital expenses (CapEx) and operational expenses (OpEx). However, a significant rise in OpEx as the fleet ages and an increase in operations and maintenance (O&M) costs due to major systems failures are impacting the wind industry [2, 3]. The failure of the main bearing (Figure 1), a high-value critical component in wind turbines, is one of the major reasons for the increase in O&M costs [4].

Owners and operators have few options to consider for main bearing O&M. Costs related to main bearing replacement, main shaft repair, and the crane and crew are significant. The total cost of a main bearing replacement can be in the range of $225,000–$400,000, depending on the turbine model and wind plant location. Also, low availability of the proper main bearing for replacement and limited resources (including cranes and technicians) are common issues in the industry, impacting O&M costs, including the following:

- Loss of wind turbine power production because of extended delays
- Unplanned maintenance events (with few repair options)
- Unavailability of spare parts and qualified repair personnel/suppliers
- Demands on site and asset management to control costs and minimize downtime

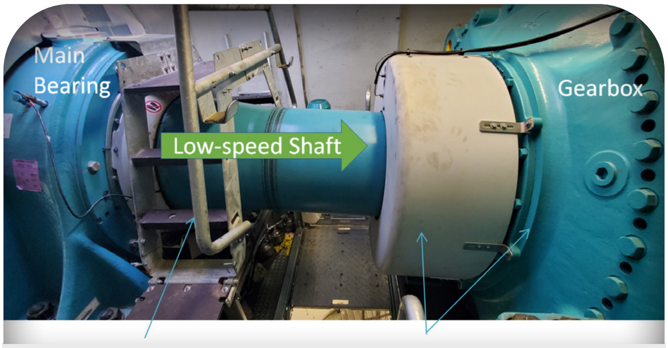

Figure 1. *The main bearing in a three-point drivetrain configuration is inclined to provide clearance between the tower and blades.*

Competition in the wind energy industry has fueled a need to increase the turbine size and capacity factor of newer models. The capacity factor is increased by modifying the wind turbine to produce the same power but at lower average wind speeds. This requires an increase in swept area and lengthening of the blades. Adapting the turbine for lower wind speed and larger swept area allows capturing more force from the wind. Also, a gearbox with a higher ratio is required to support these design changes and meet the power output requirements. The higher force captured from the wind, along with added weight from the rotor (hub and blades), results in higher aerodynamic and gravitational forces on the main bearing. These higher loads have a significant impact on main bearing durability and reliability.

To address these main bearing issues and reduce O&M costs, the wind industry is focusing on the following technical and business aspects:

- Impact of design, quality, grease, and operating conditions on main bearing service life
- Main bearing reliability and failure analysis
- Main bearing critical parts, rectifications, and recommendations for life extension

MAIN BEARING DESIGN

In a wind turbine, the main bearing supports the main shaft and transmits the reaction loads from the main shaft to the machine frame. The mainshaft assembly consists of the rotor assembly and blades upwind, the main shaft assembly with the shrink disc, and the planet carrier (with planet gears) in the gearbox downwind. The main shaft is supported by two antifriction rolling bearings, one at each end of the shaft. The two bearing locations support radial loads, and one of the bearings must locate the shaft relative to the housing and support any axial (thrust) loads imposed on the shaft. This main bearing is the “locating” bearing.

The other bearing, referred to as the “nonlocating” or “floating” bearing, must also support radial loads but should be able to move axially to accommodate any of the following conditions:

- Thermal elongation and contraction of the shaft or structure due to temperature variations
- Manufacturing tolerances of the structure
- Tolerance stack-up

The planet carrier bearings within the gearbox can be the “nonlocating” or “floating” bearings of the main shaft assembly, depending on the design configurations. Wind turbine mainshaft configurations are explained in-detail in [4].

The four-point turbine drivetrain features a “floating” bearing position (upwind; rotor side) and a “locating” position (downwind; generator side). The downwind position supports the entire thrust load and a portion of the radial load. The planet carrier bearings also function as “floating” bearings, which can move axially, allowing thermal expansion and contraction.

During wind turbine operation, the main bearing is subjected to a complex loading profile. Radial forces result from the overhung weight moments of the rotor and gearbox, and aerodynamic moments from the rotor in operation. Axial forces include rotor weight due to drivetrain tilt and thrust loads from the wind.

Wind gusts, along with intermittent changes in load as each blade passes the tower, must also be considered. For example, even when the turbine is not operating the weight of the rotor assembly is still present. The average weight of a 2.0 MW turbine rotor is approximately 180,000 lbs. Due to the incline, the resulting thrust or axial force from the weight alone is approximately 15,000 lbs.

Key factors for main bearing function and reliability are as follows:

- The roller geometry must allow the force to be distributed uniformly, without end loading.
- The bearing cage must maintain spacing and orient the rollers during transition from the nonloaded area to the load zone of the bearing. The cage must be capable of handling the loads the rollers impart to it.
- Lubrication must withstand extreme pressure and be relatively clean. Backfill of the lubricant as the rollers pass through the load zone is essential.

MAIN BEARING RELIABILITY ANALYSIS, CRITICAL COMPONENTS, AND DAMAGE MODES

EPRI, in collaboration with the National Renewable Energy Laboratory (NREL), developed the Wind Network for Enhanced Reliability (WinNER; Figure 2) web-based tool [3] (https://windturbinereliability.epri.com/), launched in 2019, which currently hosts more than 60 gigawatts (GW) of wind reliability data from 40 owners/utilities/operators worldwide [4–6]. The anonymized data from WinNER were leveraged to conduct main bearing reliability analysis and failure assessments and to provide quantifiable life extension recommendations, examples of which include the following:

- Main bearing reliability analysis and identification of life-limiting factors
- Spherical roller bearing analysis considering axial and thrust loads and critical factors impacting bearing durability and reliability.
- Main shaft and main bearing critical locations (races, cages, and rollers), failure modes, and contributing causes
- Recommendations for main bearing life extension

EPRI's WinNER database includes the data collected from 27,831 turbines worldwide. This database has 1,001 main bearing failure data points, which are mainly used for the development of reliability and health monitoring models. More than 526 wind plants covering 16 major turbine original equipment manufacturers (OEMs; including GE, Vestas, Siemens, Mitsubishi, Suzlon, Nordex, and Gamesa) with 84 different turbine types/ratings ranging from 1.5 MW to 6.2 MW are included in the database. These turbines contain main bearings supplied mostly by six different manufacturers (FAG, Koyo, NTN, Schaeffler, SKF, and Timken). Main bearing parts (races, cages, and rollers) can be manufactured at various locations and assembled before delivery to a wind plant. Hence, digitalization of a main bearing is a very complicated task for owners/operators due to the involvement of multiple OEMs, designs, suppliers, and manufacturing locations. This is a critical gap in the wind industry that owners/operators have been trying to address with NREL's and EPRI's support.

There are several key factors that influence the life expectancy of a main bearing, and the most significant ones are discussed in this paper based on WinNER database findings. This database serves two functions: First, it identifies very specific problems associated with specific turbine designs, which is useful for both current and future owners of the turbines. Second, the results can be used for reliability benchmarking at the fleet level, turbine level, and system/component level, and general maintenance issues can be inferred.

Figure 3 and Figure 4 show main bearing annual failure percentage and reliability forecasting for various operational years. Most of these data were collected from wind plants installed since 2007. Overall, the main bearing annual failure rate increased between 4 and 10 years of operation. Early main bearing failures during the first 5 years of operation were mainly due to design, assembly, and manufacturing/serial defects. Main bearing failures that occurred after 6–10 years of operation were mainly due to inner race, outer race, and roller spalling, pitting, wear/scuffing/abrasion, and cracking issues [4].

EPRI developed the Weibull Mixture model for accurate reliability forecasting [3]. As per Figure 4, main bearing S10 life (10% probability of failure) and S20 life are 10.49 years and 20.32 years, respectively. Some of the 2X–6X MW rated wind turbine main bearings have significantly higher failures rates than those of the 1.5X–2X MW platforms during the initial years of operation due to design and manufacturing issues (Figure 4). The following sections of this paper are mainly focused on identifying and understanding the main bearing life impact factors and exploring mitigation strategies to reduce future failure rates.

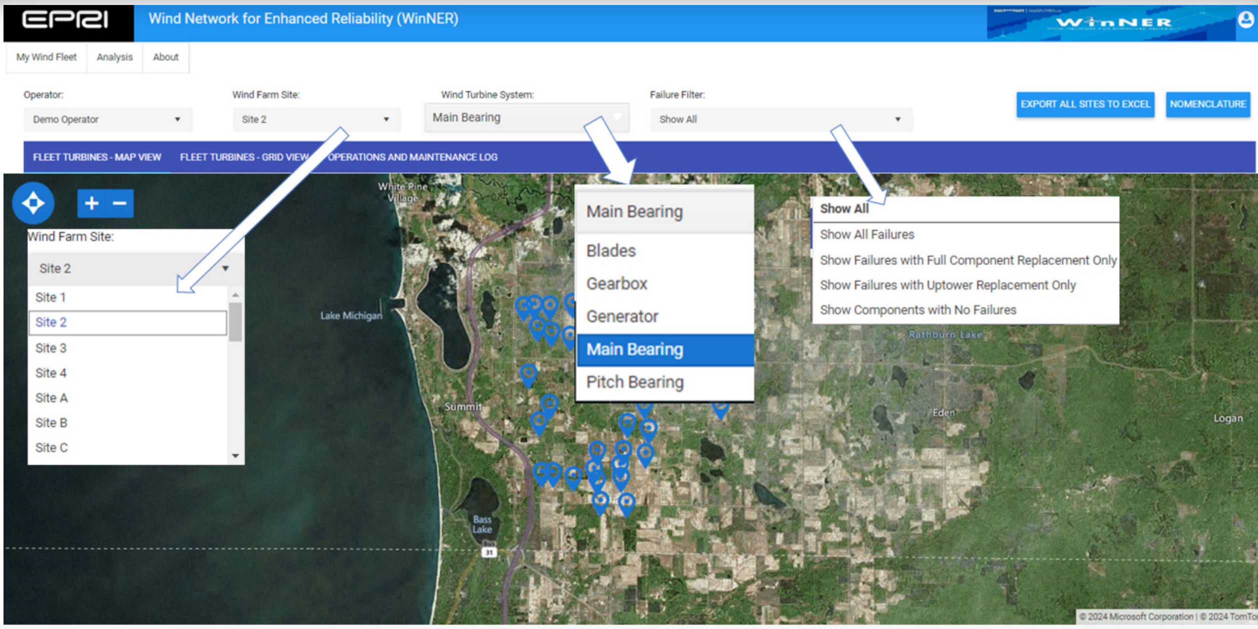

Figure 2. *Wind Network for Enhanced Reliability (WinNER) web-based tool for benchmarking, forecasting, and O&M optimization [3]*

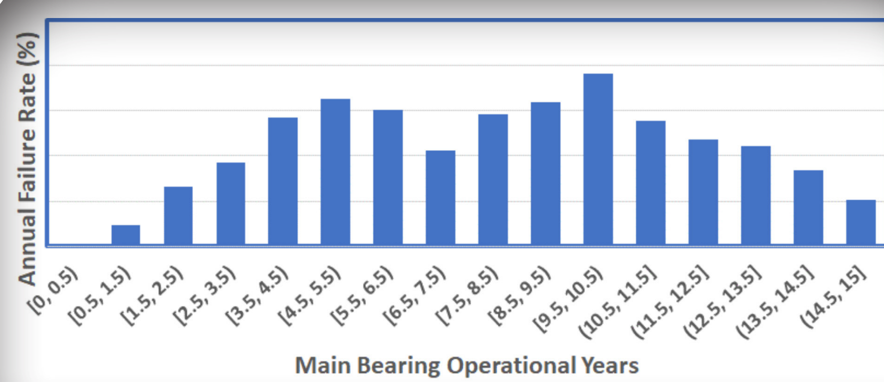

Figure 3. *Wind turbine main bearing annual failure rate vs. years of operation (data obtained from WinNER)*

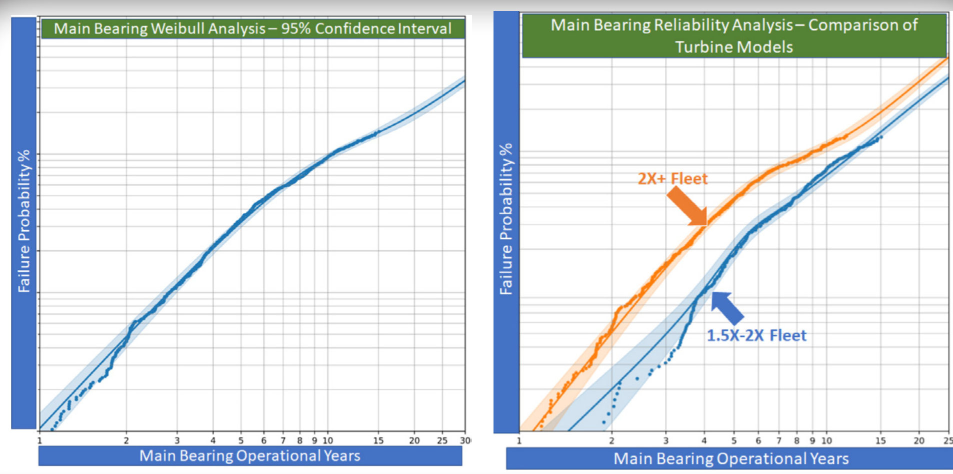

Figure 4. *Main bearing reliability forecasting assists with benchmarking, O&M prioritization, and proactive replacements to reduce operational costs.*

As shown in Table 1, most of the main bearing failures are due to inner race, outer race, and roller spalling, pitting, wear/scuffing/abrasion, and cracking issues (Figure 5) [4]. A combination of failure modes and contributing causes can usually be identified for each failure.

As an example, Figure 5 shows a three-point spherical roller main bearing that failed in service due to wear and spalling on the inner and outer races. Uneven wear and spalling on the inner race are predominantly on the downwind raceway. Normal wear of the main bearing results in debris and axial displacement, leading to its failure. The damage to the outer race shown in Figure 5 includes localized spalls that are perpendicular to the roller path and along the edges or ends of the roller path. The probable cause for this damage is inadequate or contaminated lubrication and overload. This damage has progressed to the point of radial cracking of the inner race and mainshaft, requiring an extensive repair and bearing replacement.

Table 1. *Main Bearing Critical Components, Damage and Failure Modes, and Contributing Causes.*

CRITICAL COMPONENT	ISSUE(S)	DAMAGE AND FAILURE MODE(S)	CONTRIBUTING CAUSE(S)
INNER RACE (IR)	Roller path, Spalls, Radial cracks, Axial cracks, Fracture	RCF, Subsurface initiated	Lubrication failures, Internal clearance (loss), Overload, Accelerated fatigue
	Raceway edge contact (downwind)	RCF, Surface initiated	Internal Clearance (loss), Bearing fit, Accelerated fatigue
	Debris indentations on raceways	Contaminants	Lubrication failures, Internal clearance (loss), Overload
	Fluting of raceways	Electrical erosion	Stray currents
	Slip/Creep on mainshaft	Wear (adhesive)	Overload, Bearing fit
OUTER RACE (OR)	Roller path Spalls, Cracks, Fracture	RCF, Subsurface initiated	Lubrication failures, Internal clearance (loss)
	Raceway edge contact (downwind)	RCF, Surface initiated	Internal clearance (loss), Bearing fit
	Slip in housing bore	Wear (adhesive)	Overload, Bearing fit
ROLLER(S)	Roller smearing, Skidding, Galling	Wear (abrasive)	Lubrication failures, Internal clearance (loss), Overload, Contaminants
	Roller cracking	Electrical erosion, White etch cracks	Stray currents
CAGE(S)	Cage and roller misalignment	Plastic deformation	Overload

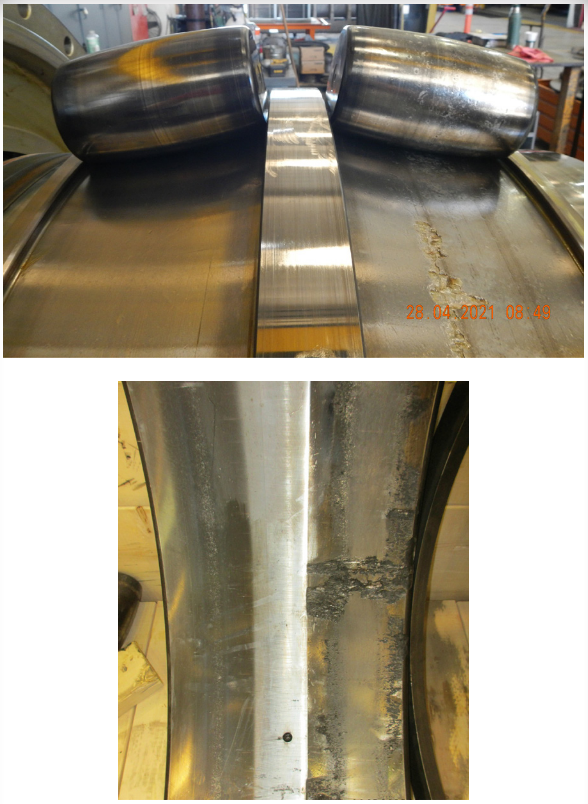

Figure 5. *Uneven damage on the main bearing inner and outer races. Spalls and cracks have developed on the downwind raceway.*

RECOMMENDATIONS FOR MAIN BEARING LIFE IMPROVEMENT

The L10 rating life calculation is the method employed by the bearing industry to determine the bearing size that is adequate to avoid fatigue failures. The L10 rating life is the fatigue life that 90% of a sufficiently large group of identical bearings operating under identical conditions can be expected to attain or exceed. The fatigue life of an individual bearing is the number of revolutions that the bearing can undergo before the first sign of metal fatigue, "rolling contact fatigue" or spalling occurs on one of the raceways (Figure 5) or rollers.

The calculated life expectancy of a bearing is based on the following assumptions/conditions:

- The bearing is of high quality with no inherent defects in material or workmanship.
- The bearing design and specification are suitable for the application.
- Bearing fits and internal clearance requirements are met. The dimensions of parts such as the shaft and housing seats are appropriate.
- The main bearing is assembled to the main shaft properly and mounted correctly within the nacelle.
- An adequate supply of clean lubricant (with desired viscosity and properties) is available to the main bearing.
- The main bearing arrangement is protected from external contaminants.
- The operating conditions are within "normal" limits.
- Recommended main bearing maintenance practices are performed.

However, main bearings in operation may not be subjected to these ideal conditions. Hence, the actual life of main bearings from field data is significantly lower than the design life (Figure 3 and Figure 4). Modification factors are applied to the bearing life calculations considering reliability, lubrication condition, etc., to determine the modified rating life. The modification factors applied to the basic rating life are based on historical data gained by the bearing OEMs.

It is recommended that the main bearing specifications include a unique manufacturing drawing and specifications, with complete traceability and documentation that includes the following data:

- Radial internal clearance
- Load rating
- Speed limit
- Outer race material certification, source, manufacturing facility, and heat treatment documentation, with unique batch and serial numbers
- Roller material certification, source, heat treatment documentation, end finish, and coating, with unique batch numbers
- Inner race material certification, source, manufacturing facility, and heat treatment documentation, with unique batch and serial numbers
- Cage material certification, source, and manufacturing facility
- Documented use of components for each bearing (bill of materials)
- Unique serial numbers for assembled bearings

- Inspection and testing
- Packaging
- Shipping instructions
- Storage requirements (instructions)

This comprehensive main bearing data will assist owners/operators with asset digitalization and management, reliability tracking, and reducing O&M costs.

Below are the main bearing life extension options that can assist owners/operators in reducing their O&M costs [4]:

- Automatic lubrication: auto refill of grease
- Hot oil flush and grease refill: removal of metallic debris
- Optimum time to replace grease: replace grease based on condition and quality by leveraging grease sampling results obtained every 6 months
- Lubrication and system upgrades: replace with better grease if there is an available option
- Smart curtailment/derate: may reduce main bearing loads and damage propagation rate
- Supplemental grounding strap at the main bearing location to mitigate stray current issues.

Grease cannot make up for design, material, and manufacturing defects of the main bearing components, but a lubricant flush, clean, and refill can slow the progression of damage (at an approximate cost of 1% of a main bearing replacement). Figure 6 shows how a grease flush on a 2X-MW turbine main bearing and switching over to another grease type have reduced vibration. The small wrenches symbolize when the owner/operator added/flushed the grease.

Laboratory grease sample analysis is performed as a part of the regular maintenance cycle and to satisfy warranty and end-of-warranty requirements. Grease sample analysis at 6-month intervals may not be frequent enough to provide reliable trending data. Monitoring technologies (such as machine learning model based on temperature data, and vibration) combined with grease sample results may provide more visibility of main bearing health [4].

Also, it is recommended for owners/operators to maintain strategic relationships with bearing OEMs, grease suppliers, lubrication system suppliers, and main shaft repair specialists for inventory management.

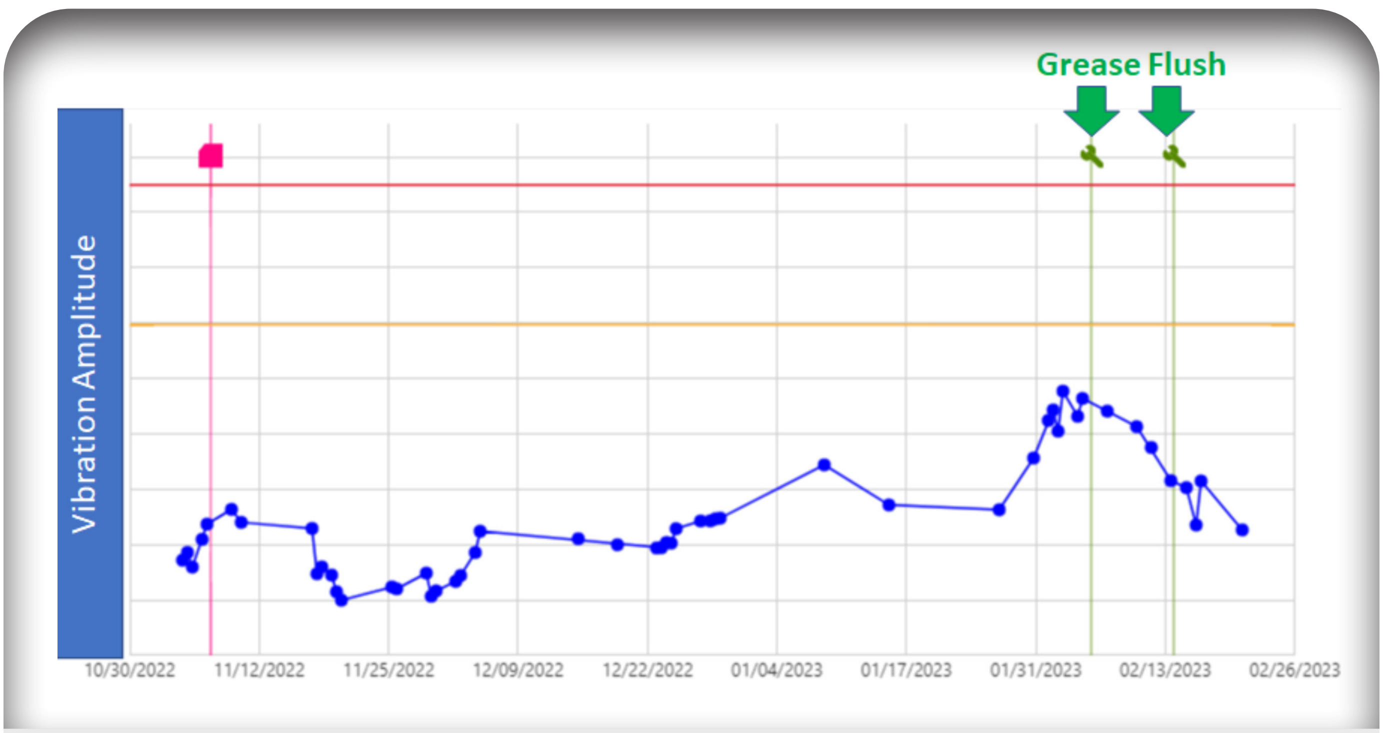

Figure 6. *Grease flush reduced main bearing vibration on a 2X turbine.* Image from Consumers Energy

SUMMARY AND NEXT STEPS

To increase the capacity factor, the wind energy market has evolved to locate turbines at sites with lower wind speeds (Wind Class). Utilization of longer blades—to increase the swept area—may increase the aerodynamic forces and gravitational load (weight) acting on the main bearing, impacting its durability and reliability.

As per the WinNER web-based reliability tool, the main bearing S10 life (10% probability of failure) and S20 life (desired design life) is 10.49 years and 20.32 years, respectively.

Typically, in the selection of the main bearing, load calculations and assumptions are made for representative operating conditions. The operating conditions and actual loads for a specific site can differ, resulting in the need to evaluate the lubricant properties and relubrication interval (grease life). Improving the effectiveness of the main bearing lubricant and adjusting the relubrication interval will optimize the load carrying capacity of the main bearing, improving its service life.

Main bearing life can be extended by identifying damage in its early stages using machine learning and data analytics techniques and by implementing life-extension actions such as regreasing, grease flushing/replacement, smart curtailment/derating, and adding supplemental grounding straps for stray current issues. The benefits of main bearing early damage detection and life extension include:

- Low-cost repairs rather than running the equipment to catastrophic failure.
- O&M prioritization and optimization of turbine maintenance efforts.
- More preventive O&M actions and fewer corrective maintenance events.
- Crane mobilization and savings by bundling the main bearing replacements with other major system replacements.

"WinNER database allowed us to justify our funding requests for all major component replacement without having had any failures to date. This will prevent extended downtime by allowing us to secure the appropriate number of critical spares on long-lead components"

~Eric Robinson, CMRP,
Principal Renewables Engineer,
Consumers Energy

NREL and EPRI to continue to work on main bearing reliability and that of other major systems (blades, pitch, gearbox, generator, inverters, and transformers) and life improvement assessments focusing on newer and larger wind turbine models (2X–6X MW). This includes collaborating with turbine OEMs and owners/operators in identifying mitigation strategies to reduce O&M costs. Also, NREL and EPRI to focus on linking wind turbine reliability with turbine-specific wind characteristics (such as wind speed, turbulence intensity, and shear) and operating loads (using supervisory control and data acquisition, SCADA data) to develop and implement advanced performance and monitoring technologies. Details of these efforts and key findings will be included in future reports.

REFERENCES

1. Wood Mackenzie, Forecasts - Global Wind, 2024
2. Pulikollu R. V. et al., *Wind Turbine Predictive Analytics—Technology Landscape*. EPRI, Palo Alto, CA: 2019. 3002013769.
3. *Wind Network for Enhanced Reliability (WinNER) Web-Based Tool*. EPRI, Palo Alto, CA: 2021. 3002020805. https://www.epri.com/research/products/3002020805
4. Pulikollu R. V. et al., *Wind Turbine Main Bearing Reliability Analysis and Recommendations for Life Improvement: Design, Manufacturing, Grease, and Operating Conditions Impact on Main Bearing Life.* EPRI, Palo Alto, CA: 2023. 3002026662. https://www.epri.com/research/products/000000003002026662
5. Pulikollu R. V. et al., *Wind Turbine Gearbox Reliability, Damage Prediction, and Recommendations for Life Improvement: Digitization of Wind Assets to Reduce O&M Costs*. EPRI, Palo Alto, CA: 2019 3002016434. https://www.epri.com/research/products/000000003002016434
6. Pulikollu R. V. et al., *Wind Turbine Generator Reliability Analysis to Reduce Operations and Maintenance Costs*. EPRI/NREL. 2023. 3002026844. https://www.nrel.gov/docs/fy23osti/86721.pdf https://www.epri.com/research/products/000000003002026844
7. Hart et al. *Main Bearing Replacement and Damage – A Field Data Study on 15 Gigawatts of Wind Energy Capacity*. Golden, CO; National Renewable Energy Laboratory. 2023. NREL/TP-5000-86228.

ACKNOWLEDGMENTS

This article was prepared by Rajasekhar V. Pulikollu and Lili Haus (EPRI), Jeff Mclaughlin (Machine Building Specialists), and Shawn Sheng (National Renewable Energy Laboratory [NREL]).

DISCLAIMER OF WARRANTIES AND LIMITATION OF LIABILITIES

EPRI PREPARED THIS REPORT.

This work was authored in part by the National Renewable Energy Laboratory, operated by Alliance for Sustainable Energy, LLC, for the U.S. Department of Energy (DOE) under Contract No. DE-AC36-08GO28308. Funding provided by U.S. Department of Energy Office of Energy Efficiency and Renewable Energy Wind Energy Technologies Office. The views expressed in the article do not necessarily represent the views of the DOE or the U.S. Government. The U.S. Government retains and the publisher, by accepting the article for publication, acknowledges that the U.S. Government retains a nonexclusive, paid-up, irrevocable, worldwide license to publish or reproduce the published form of this work, or allow others to do so, for U.S. Government purposes.

This is an EPRI Technical Update report. A Technical Update report is intended as an informal report of continuing research, a meeting, or a topical study. It is not a final EPRI technical report.

About EPRI

Founded in 1972, EPRI is the world's preeminent independent, non-profit energy research and development organization, with offices around the world. EPRI's trusted experts collaborate with more than 450 companies in 45 countries, driving innovation to ensure the public has clean, safe, reliable, affordable, and equitable access to electricity across the globe. Together...shaping the future of energy.

EPRI CONTACTS

RAJASEKHAR PULIKOLLU, *Technical Executive*
980.495.7425, rpulikollu@epri.com

BRANDON FITCHETT, *Program Manager*
704.595.2047, bfitchett@epri.com

For more information, contact:

EPRI Customer Assistance Center
800.313.3774 • askepri@epri.com

3002029874 **November 2024**

EPRI
3420 Hillview Avenue, Palo Alto, California 94304-1338 USA • 650.855.2121 • www.epri.com