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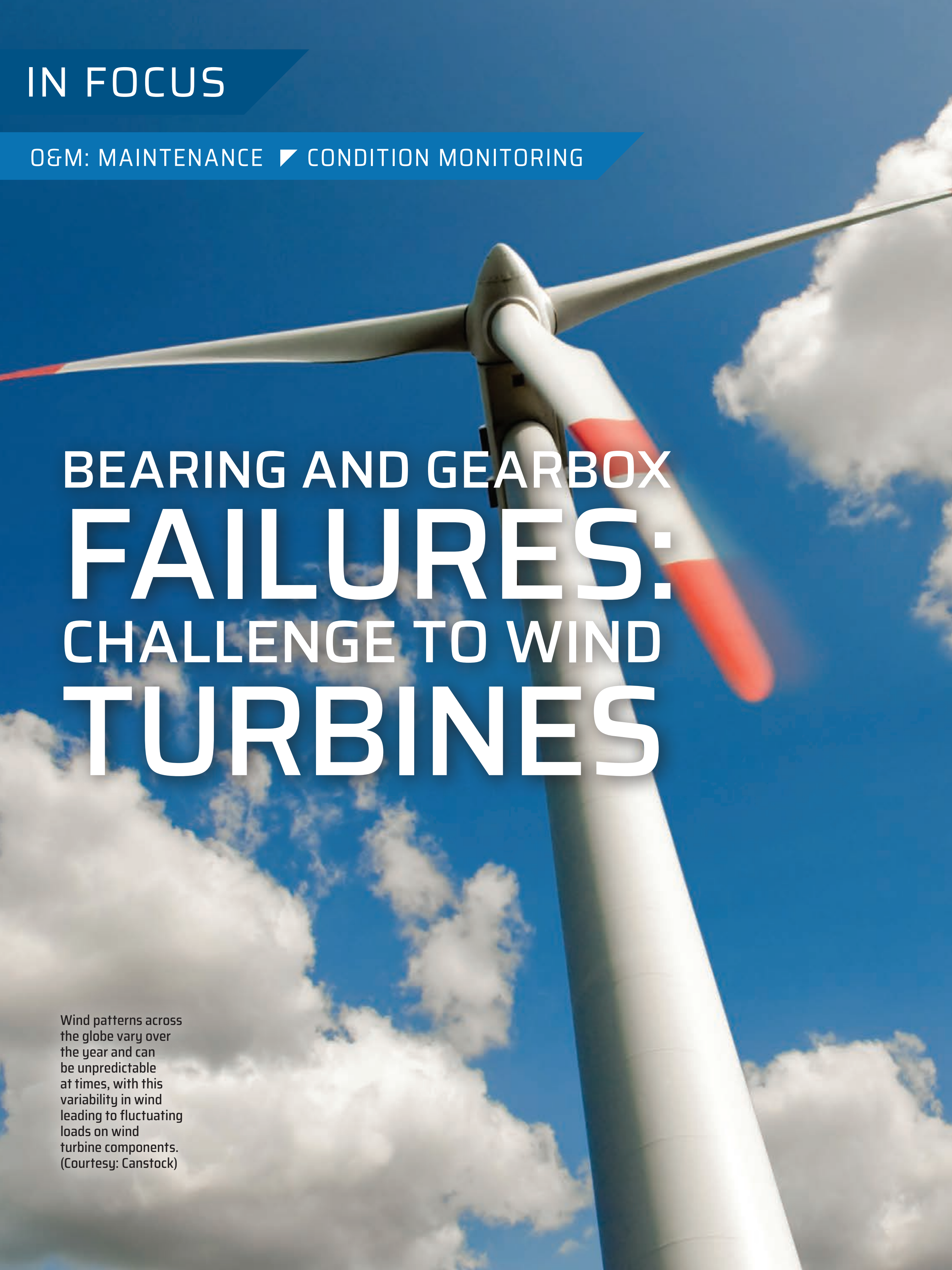
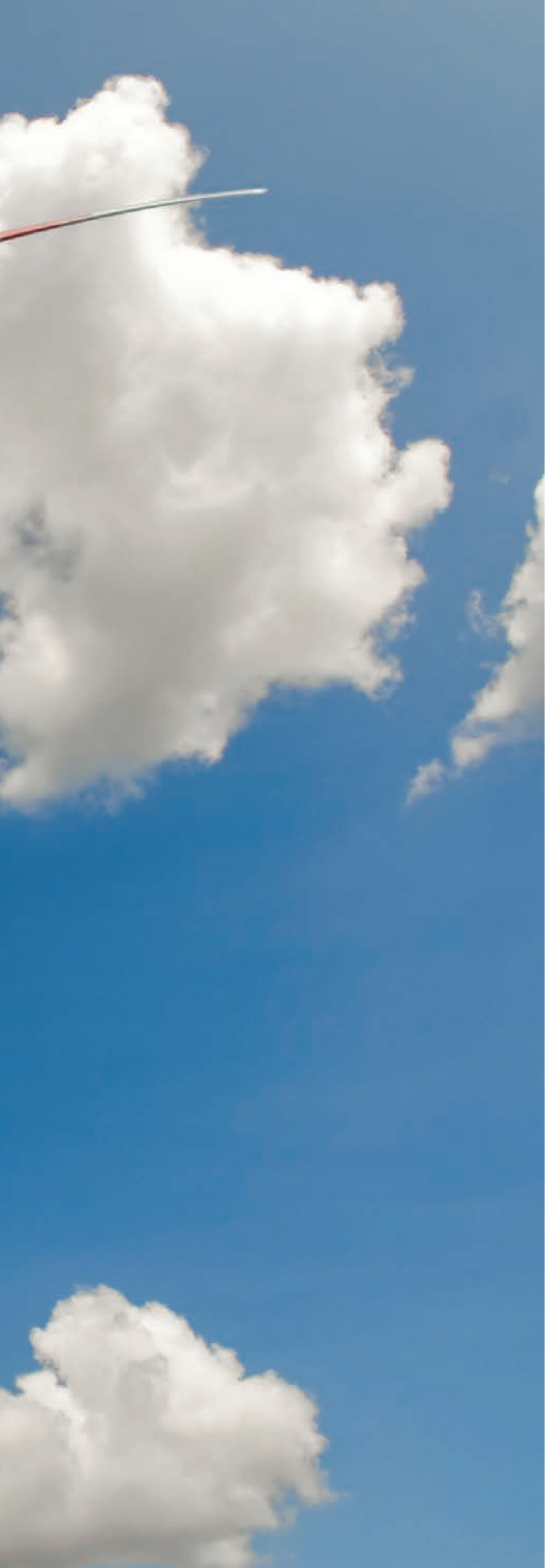
BEARING AND GEARBOX FAILURES: CHALLENGE TO WIND TURBINES



Wind patterns across the globe vary over the year and can be unpredictable at times, with this variability in wind leading to fluctuating loads on wind turbine components. (Courtesy: Canstock)



The review of current trends in wind-turbine bearings is important, not only for reducing the cost of energy, but also for ensuring the future of sustainable and zero-emission energy sources.

By ANDREA R. AIKIN

With ever increasing energy requirements, the energy sector is seeing an unparalleled growth in renewable energy production with wind energy in the lead. Land-based, utility-scale wind farms offer the lowest priced energy source currently available at between 2 to 6 cents per kilowatt-hour. [5]

As of the fourth quarter 2019, the American Wind Energy Association (now the American Clean Power Association) reported there are 105,583 MW of wind energy operating in the U.S. with more than 59,800 wind turbines spinning across 41 states and two U.S. territories. [4] In 2019, 7.3 percent of U.S. energy demand was met using wind energy. [1] This percentage could be increased to 20 percent by 2030 and to 35 percent by 2050. [2]

A wind turbine creates electricity when wind flows across the turbine blade and spins the rotor. The rotor is connected to a generator directly in a direct drive turbine or through a shaft and a series of gears (i.e., a gearbox) that speed up the rotation and allow for a physically smaller generator (see Figure 1). [15] This translation of aerodynamic force-to-rotation of a generator is what creates electricity.

Wind patterns across the globe vary over the year and can be unpredictable at times, with this variability in wind leading to fluctuating loads on wind turbine components. A typical wind turbine consists of more than a dozen bearings that are expected to work simultaneously and continuously for many years. As a result, wind-turbine bearings and gearboxes are often susceptible to failure well before their designed service lives.

Bearing failures in wind turbines are a major cause of downtime in energy production for unplanned maintenance, repairs, and replacements. This failure type is a primary cost and results in higher operations and maintenance (O&M) costs for the energy operator and in higher utility bills for the customer. The National Renewable Energy Laboratory's (NREL) Gearbox Reliability Database (GRD) shows that 76 percent of gearboxes failed due to bearings, while 17 percent failed due to gear failures. [11] This shows the importance of reliable bearings and gearboxes for wind-turbine operations to the economy and society.

WIND TURBINE BEARINGS

The gearbox in a wind turbine consists of several bearings that translate the wind energy from the spinning blades into electrical energy (see Figure 1). In the 21st century, bearings are one of the most critical mechanical/tribological components used in a wide range of applications, including aerospace, automotive, energy, medical devices, sporting equipment and so on.

Wind-turbine drivetrains include different types of bearings (see Table 1). Bearings and gearboxes in wind turbines are designed and certified to last for at least 20 years; however, only a small percentage survive that long in the field. As a result, many bearing OEMs are taking special interest in bearings used in wind-turbine applications with the desire to design stronger, tougher, and more reliable bearings.

STLE-member Shawn Sheng, a senior engineer at NREL in Golden, Colorado, notes that, while gearboxes "do not fail as often as electronic components in a turbine, they appear to be the costliest to maintain throughout a turbine's 20-year design life." If not detected and mitigated early enough, Sheng said these failures "can lead to entire replacement of these gearboxes, which require costly crane rental expense, in addition to revenue loss, capital cost on new or upgraded components, labor, and other costs, which dramatically increase the cost of energy for wind power, impacting offshore wind even more."

In 2007, NREL established the Gearbox Reliability Collaborative (GRC) to foster understanding of the root causes of premature gearbox failures and to improve gearbox reliability. [6] GRC research has found the faults in most prematurely failed gearboxes are related to bearing failures in the intermediate and high-speed sections, with much of that failure occurring in as little as 5 percent to 20 percent of the bearing's design life. [6]

"Bearings are key elements that enable rotational motion and support radial and axial loads in a wind turbine," said STLE-member Harpal Singh, principal engineer at Sentient Science in West Lafayette, Indiana.

Singh noted bearing failures in wind turbines can be expensive due to lost production, replacement component costs, and maintenance costs, with the total cost of wind-turbine gearbox replacement varying depending on the turbine location, turbine type, gearbox type, etc. Gearbox failures on land-based turbines are assumed "to cost about $250,000-$300,000 per failure event."

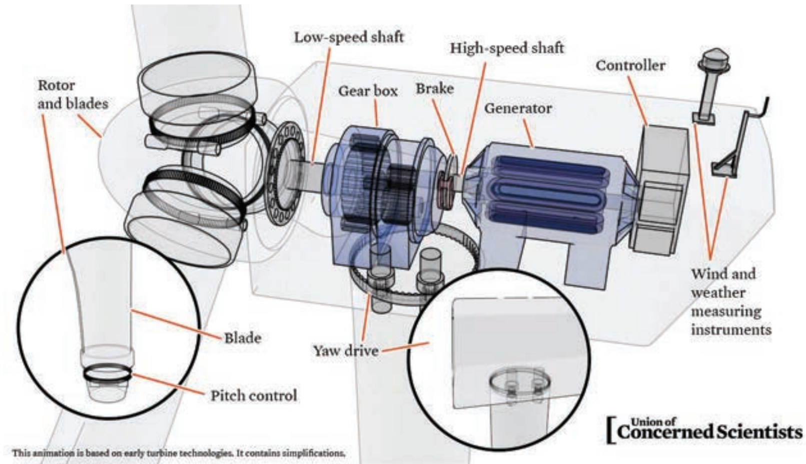


Figure 1: Simplified view of components of an upwind-facing, horizontal-axis wind turbine with a gearbox drive. [15] (Courtesy: Union of Concerned Scientists, www.ucsusa.org.)

TYPES OF BEARING FAILURES IN WIND TURBINES

Sheng reported NREL's research "tries to help industry improve wind-turbine drivetrain reliability, both inherent and operational, through testing, modeling/analysis, failure mode investigation and O&M research, leading to reduced O&M cost and making wind power more cost competitive." Sheng focuses on failure data collection and statistical analysis, fault diagnostics, and prognostics research.

NREL's research on wind power reliability focuses on gearboxes, blades, and how turbines interact with the electric grid. [14] NREL collects gearbox failure data in its GRD, whose goal is to quantify the magnitude of the problem and identify top failure modes and root causes, while directing wind-turbine gearbox reliability research and development and providing a benchmark for evaluating technology advancements. [11] Main bearing failures caused by micropitting, white etching cracks in gearbox bearings, and generator bearing failures are identified as research priorities.

Singh identified five of the most common failure modes observed in wind-turbine bearings:

- **Axial cracking:** Characterized by the presence of a crack in the axial direction largely caused by improper fits, improper shaft grooving, rotation of rings, and microstructural alterations (also called white etching cracks [WECs]) in bearing material.
- **Scuffing/smearing:** A type of adhesive wear that occurs in two mating surfaces when material transfers from one surface to another under frictional heating.
- **Spalling:** Characterized by pitting and flaking of material from the raceways and rolling elements caused by "geometric stress concentration from deflection and misalignment, inclusions and defects in the material subsurface and high localized stresses from nicks, dents, and debris."
- **Micropitting:** Or surface-initiated fatigue, is caused by inadequate lubrication resulting in the contact surfaces no

Bearing Type	Turbine Drivetrain Component
Ball	Yaw bearings Pitch bearings Generator
Cylindrical roller	Gearbox
Tapered roller	Gearbox Main shaft Pitch bearings
Spherical roller	Main shaft Gearbox

Table 1: Different bearing types used in wind-turbine drivetrains. (Source: Adapted from Andrew, J.M. (2019), "Fundamentals of wind turbines," TLT, 75 (8), pp. 32-40. Available at https://www.stle.org/files/TLTArchives/2019/08_August/Webinars.aspx.)

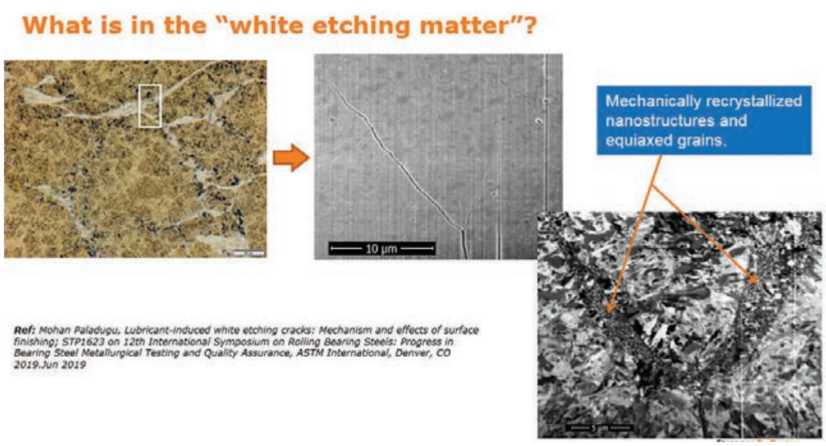


Figure 2: White etching matter observed under an optical microscope. (Courtesy: Mohan Paladugu, "Lubricant-induced white etching cracks: Mechanism and effects of surface finishing," STP1623 on 12th International Symposium on Rolling Bearing Steels: Progress in Bearing Steel Metallurgical Testing and Quality Assurance, ASTM International, Denver, Colo., June 2019.)

longer being separated, and leading to asperity shear, plastic deformation, and break off. Asperity breaking causes micro-spalls, which can grow into macrospalls/spalling over time.

- **Dents/indentations:** Result when the lubricant is contaminated with foreign abrasive particles or when debris generated within the system is entrapped between raceways and rolling elements.

A 2016 Department of Energy report noted some bearing failures and their underlying physics are not well understood and remain a research priority. [6] Main bearing failures caused by micropitting, WECs in gearbox bearings, and generator bearing failures are identified as research priorities, but until the failure modes are well understood, the mitigation strategies being developed might only partially address these failures. [6]

Sheng identified scuffing and axial cracking as the top two failure modes for gearbox bearings, while fracture and cracking appear to be the top failure modes for gearbox gears. Sheng noted axial cracks or WECs have attracted research attention, but "there is still no consensus on the root causes and solutions to completely get rid of this failure mode, although case-carburized bearing steel with increased retained austenite and diamond-like carbon coating appear helpful with its mitigation." While axial cracking occurs on the surface, WECs, typically thought of as precursors to axial cracking, occur in the subsurface.

WHITE ETCHING CRACKS AND BEARING FAILURE ANALYSIS

Bearings in wind-turbine applications are known to show premature damage, typically as cracks in the bearing steel, with the crack faces often showing evidence of white etching matter. Based on their appearance, these are called WECs, and they are known to cause premature damage to the bearings. [9] WECs also are called white structure flaking (WSF), irregular white etching cracking (Ir-WEC), and brittle flaking. The cracks are thought to form first from the intensity of local shear stress, then the white etching matter is thought to form later from the rubbing of the crack faces against each other. [9,10]

While axial cracking occurs on the surface, Singh described WECs as the "premature bearing failures caused by extensive subsurface crack networks associated with altered microstructure." WECs appear white when etched with Nital and observed under an optical microscope (see Figure 2). They show a grain size of 5-300 nanometers, with a hardness 10-50 percent higher measured in microstructure adjacent to these cracks, compared to the unaltered microstructure.

In a 2017 Tribology Letters article, white etch areas were found to precede crack formation, and cracks are prerequisites for white etch formation. [3] The article confirmed the microstructural alterations detected in the studied bearings were observed to have different crack morphology that could be initiated by different mechanisms, including material, mechanical, thermal, and chemical phenomenon. [3]

While what drives the occurrence of WECs in bearings is still being debated, Singh noted it is thought to be driven individually or by a combination of multiple factors, including:

- The presence of hydrogen resulting from lubricant decomposition, stray current, corrosion or water.
- Mechanical and tribological factors, including high, normal, or transient loads or frictional stress.
- Electrothermal and electrical effects.

Mohan Chand Paladugu, a materials science specialist with The Timken Co. in North Canton, Ohio, noted WECs "are seen as the main damage mode" for bearing damages from wind-turbine gearboxes and are "known to cause very premature bearing damages." As previously noted, Paladugu confirmed premature bearing damage adds "significant costs to the maintenance of wind turbines."

In WEC-induced failures in wind-turbine gearboxes, Paladugu noted, "subsurface cracks are seen in the bearing raceways, and these cracks seem to be oriented in the over-rolling direction." The white appearance of some of these cracks, in optical metallography observations, is the cause of the WEC name.

In recently published articles, WEC damage was generated in metal subsurfaces under the influence of subsurface shear stresses but was caused by the tribochemical reactions occurring at the rolling contact. [12,13] In other words, although WECs form in the subsurface, their formation is a surface-driven phenomenon. This was demonstrated by applying abrasive particles on the raceway surfaces and testing the bearings in an oil that causes WECs. [13]

Paladugu concurred WEC damage is caused by a combination of multiple factors, including "significant slip at the rolling contact, combined with reactive oil additive chemicals, in the lubricant or reactive oil additive chemicals in the lubricant, combined with stray electric currents." Tribochemical reactions are thought to drive atomic hydrogen into the steel, which results in deformation damage and cracking in the raceway subsurfaces.

Paladugu noted it is possible to generate white etching material through other ways, "but those ways do not seem to cause premature bearing damages under the typical loads in application."

Testing the role of lubricants in generating WECs found bearings were damaged prematurely when the tests were performed in an oil with reactive additives. [12,13] The reports concluded that a tribofilm is formed, as a consequence of reactive additive elements, in the lubricant oil, and associated tribochemical reactions drove the formation of the subsurface cracks in steel. [12,13,14]

While WEC damage can be mitigated by avoiding reactive lubricant additives, Paladugu noted the lack of the reactive additives might result in other problems such as micropitting of gears and bearings. Chemically modifying the steel surfaces at the rolling contact is one way to avoid WEC damage by avoiding the tribological reactions. Paladugu listed using black oxidized bearing components or using bearing components made of high chrome steels that form surface passivation oxide layers as ways to avoid these tribological reactions.

NREL's research on wind power reliability focuses on gearboxes, blades, and how turbines interact with the electric grid. (Courtesy: Canstock)

Paladugu said current trends in bearing designs that would improve bearing performance include "preloaded tapered rolling bearings, where roller skidding, axial and radial loads can be better controlled."

COMPUTATIONAL SOLUTIONS FOR DETECTION, PREDICTION OF EARLY FAILURES

Computational solutions include algorithms or models that detect or predict impending failures of components. Sheng reported "various computational solutions are investigated in the literature for diagnostics and prognostics of component failures," and although more of this work has been performed in applications other than wind turbines, some has been done. Sheng divided these solutions into "data domain, physics domain, or hybrid data-physics domain integrated approaches." In regard to the wind industry, Sheng found that, for field deployment, diagnostic solutions in the data domain are more mature and widely used than prognostics, but both areas have been and will continue to be active areas of research in the foreseeable future.

Reduced O&M costs can be achieved by wind-power plants through prognostics and health management (PHM) technologies, but prognostics activities are still generally at the research and development stage. [7] The focus of the prognostics research, in relation to wind turbines, has been on remaining useful life (RUL) prediction. [7] This research has indicated bearing axial cracking is the prevalent wind-turbine gearbox failure mode experienced in the field, while, in contrast, rolling contact fatigue is normally the only failure mode represented in the bearing design life calculation. The probability of failure is used as a component reliability assessment and RUL prediction metric and can be expanded to other drivetrain components. PHM technologies can be applied to both land-based and offshore wind turbines. [7]

The wind industry has been exploring ways to mitigate the impacts of these bearing and gearbox failures in wind turbines in areas ranging from design to new materials or lubricants and to O&M practices. [8] Condition-based maintenance, accomplishable under a PHM framework, has been explored for its ability to improve O&M practices in wind turbines. Numerous future research opportunities exist for wind turbine PHM technologies. [8]

Sheng noted computational solutions enable a "maintenance paradigm shift from time or usage-based maintenance to condition-based or predictive maintenance." These types of computational solutions can help improve efficiency, reduce human errors, and save costs. While validation is challenging, cross-validation during the development of computational solutions is a typical approach, which uses a portion of the data for training and another portion for testing.

Comparing model predicted outputs with future actual measurements, from the modeled physical phenomena or system, also is another possibility. It is always better to start with something simple, integrate validation in model development, and then gradually increase the system complexity.

CONCLUSION

The review of current trends in wind-turbine bearings is important, not only for reducing the cost of energy, but also for ensuring the future of sustainable and zero-emission energy sources. As the wind industry adopts more advanced data analytics capabilities, more cost-effective prevention and maintenance can be performed to enhance wind energy. Sheng said "wind power has become an integrated piece of the energy solution around the world, and its capacity will continue to increase, helping to address global climate change."

FURTHER READING

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