U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

WIND AND WATER POWER PROGRAM

Wind Turbine Drivetrain Reliability Collaborative Workshop

A Recap

Authors:
J. Keller, S. Sheng, and J. Cotrell
National Renewable Energy Laboratory

A. Greco
Argonne National Laboratory

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Foreword

The Wind Turbine Drivetrain Reliability Collaborative Workshop was convened by the National Renewable Energy Laboratory (NREL), Argonne National Laboratory, and the U.S. Department of Energy to explore the state of the art in wind turbine drivetrain mechanical system reliability as well as research and development (R&D) challenges that if solved could have significant benefits.

The workshop was held at the Research Support Facility on NREL's main campus in Golden, Colorado, from February 16–17, 2016. More than 120 attendees participated from industry, academia, and government. Plenary presentations covered wind turbine drivetrain design, testing, and analysis; tribology—the science and engineering of interacting surfaces in relative motion—and failure modes; and condition monitoring and data analytics. In addition to the presentations, workshops were held in each of these areas to discuss R&D challenges. This report serves as a summary of the presentations, workshops, and conclusions on R&D challenges in wind turbine drivetrain reliability.

The presentations are available at http://www.nrel.gov/wind/grc/meeting_drc_2016.html.

Acknowledgments

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Introduction

The cost of energy from wind has declined tremendously during the past two decades [1] due to a combination of lower capital costs, higher production, and more efficient operation. As designs have improved, downtime has been reduced [2]; logistics are handled more efficiently; and availability in excess of 95% is routinely achieved, and up to 98% is even reported [3]. But these gains are not without significant effort, as evidenced by the increase in wind power plant operation and maintenance (O&M) costs as wind power plants age [4, 5]. Wind power plant O&M is a $2 billion to $3 billion annual market in the United States and consumes up to one-third of revenue [4–6]. Total fleetwide O&M costs are increasing 5% to 10% per year and will continue to grow as the installed capacity grows, potentially surpassing the value of new turbine sales within a decade. Owners and operators report that these O&M costs, a significant portion of which are related to drivetrain reliability [3], are higher than expected for existing wind power plants—to the extent that they reduce the anticipated profitability of new wind power plants and thus can discourage their development.

Reliability is the ability of a system or component to perform its required functions under stated conditions for a specified period of time [7]. Reliability is a fundamental discipline that affects all aspects of the cost of energy. A lack of reliability increases capital expenditures through overdesign, excessive prototyping and testing, and warranty and insurance requirements; increased financing costs due to uncertainties; operational expenditures from both scheduled and unscheduled events; and annual energy production through lack of reliability and subsequent unavailability. The desire and expectation of the industry is that drivetrain components have a 20-year life span following the notional "bathtub" reliability curve, as shown in Figure 1. Today's reality is that many component failure rates are simply higher than expected, and they could potentially increase as turbines age. The desired end state of tomorrow is that drivetrain reliability is improved such that a more predictable bathtub curve is followed, with opportunities for life extension beyond 20 years.

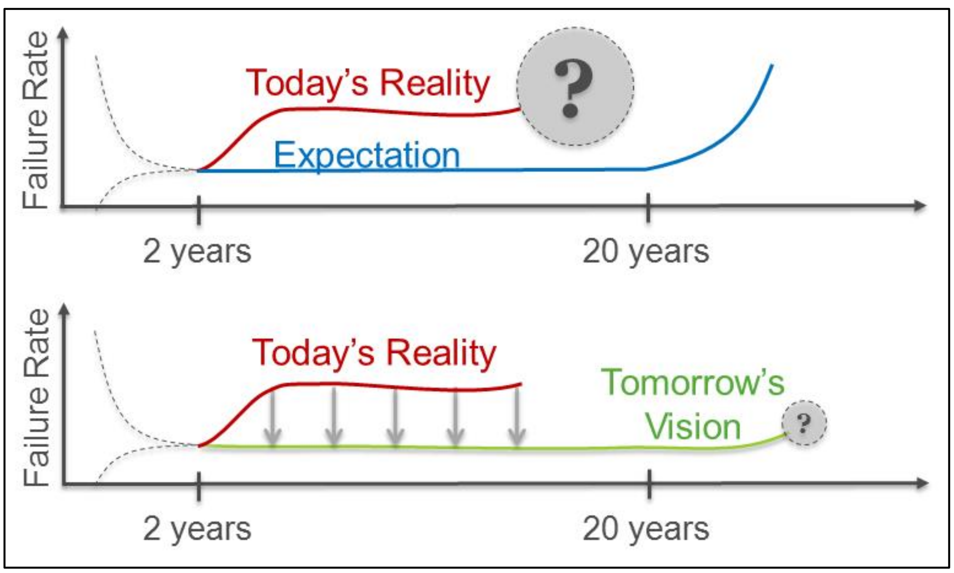

Figure 1. Reliability expectation: today's reality and tomorrow's vision

Background and Significance of Research

The U.S. Department of Energy (DOE) has been investing in wind turbine gearbox and blade reliability research for nearly a decade [8, 9]. In the area of drivetrains, the Gearbox Reliability Collaborative (GRC) was established in 2007 at the National Renewable Energy Laboratory (NREL) with the key goal of understanding the root causes of premature gearbox failures and improving their reliability. To date, the GRC has used a 750-kilowatt drivetrain for testing and analysis, including the dedicated design of a nonproprietary gearbox with cylindrical roller bearings in the planetary section [10]. The test program focused on planetary section load-sharing characteristics, examining the detrimental effect of rotor nontorque loads on planetary load sharing and predicted fatigue life and the risk of bearing skidding [11, 12]. The GRC has publicly disseminated its engineering drawings, gearbox models, test data, and results [13]. The final element of the research program on the 750-kilowatt drivetrain is a redesign and retest of the gearbox with tapered roller bearings in the planetary section to evaluate if this can improve load-sharing characteristics and predicted fatigue life [14].

Shortly after the GRC design and testing program began, NREL and Argonne National Laboratory (Argonne) held public workshops in the areas of tribology and lubricants, condition monitoring, and gear and bearing failure modes [15–19]. Vibration and oil condition monitoring research was conducted along with other testing of the 750-kilowatt drivetrain [20, 21], including publicly disseminating vibration data from both healthy and damaged gearboxes [22]. Typical wind turbine gearbox failure modes were summarized through the collection of data from industry contributions. The predominant drivetrain component failure modes are not accounted for in design standards, typically not attributable to quality control, complex in nature, and generally independent of specific component suppliers. The majority of the damage in prematurely failed gearboxes as reported by industry was related to bearing failures in the intermediate and high-speed sections [23], with a significant portion due to a failure mode often called axial cracking or white etching cracks (WECs). This failure mode is not related to rolling contact fatigue, and it can occur in as little as 5%–20% of the bearing's design life [24, 25].

Accordingly, in partnership with industry, both NREL and Argonne are now investigating the WEC failure mode. More recent GRC tests focused on the high-speed shaft tapered roller bearing pair [26], examining load sharing and roller sliding within them [27–29]. Argonne re-created WECs in a benchtop test rig and proposed a cumulative energy life-span criterion related to frictional sliding energy [30, 31]. NREL is designing instrumentation and planning testing in a 1.5-MW turbine to uncover the environmental conditions, operational situations, and control modes that may relate to the cumulative energy life-span criterion [32]. This joint laboratory-industry research program has the potential to significantly reduce bearing failures in wind turbine gearboxes. Similarly, because of industry feedback and suggestions, NREL has also recently modeled main bearing loads and motions to examine factors related to premature main bearing failures [33] because these failures contribute to O&M costs almost equally as do gearbox failures.

Wind power plant owners and operators, service providers, and turbine suppliers have become especially interested in combining physics-based models with data-driven models for predicting remaining useful life, improving wind power plant availability, and reducing O&M costs [34]. Therefore, NREL and partners have begun modeling and analyzing supervisory control and data acquisition (SCADA) system data [35, 36] as a complementary approach to condition monitoring to improve the effectiveness of O&M practices. The Internet of Things, big data management tools and infrastructure, predictive analytics methods, and cloud computing provide new tools and opportunities for utilizing wind power plant operational data to achieve these goals.

Workshop Agenda and Report Outline

The activities described above form the historical foundation of the DOE-funded wind turbine reliability R&D program. The 2016 Wind Turbine Drivetrain Reliability Collaborative Workshop was intended to help define the next phase of the R&D agenda. The seminar consisted of 4 plenary sessions with 13 speakers along with breakout sessions in the areas of drivetrain design, testing, and analysis; tribology and failure modes; and condition monitoring and data analytics. For the purposes of the workshop and this report, the scope of the drivetrain was limited to the mechanical systems from the rotor hub to the generator. The electrical systems that are sometimes considered as part of the drivetrain are not included; although these systems are as critical to performance as the drivetrain, their failure modes are vastly different. Table 1 details the seminar's agenda. Following sections of the report summarize the plenary sessions and R&D recommendations as a result of the discussions in the breakout sessions.

Table 1. Seminar Agenda

Time	Topic	Speaker and Affiliation
8:30 a.m.	Welcome and Opening	Paul Veers, NREL
	Workshop Goals and Organization	Jonathan Keller, NREL
	DOE Reliability Program Overview and Status	Nick Johnson, DOE
Design, Testing, and Analysis Plenary Session		
9:00 a.m.	Closing the Gap Between Design and Operational Requirements in Gearbox Engineering	Zhiwei Zhang, Romax Technology
	Toward Higher Gearbox Reliability and Torque Density	Jon Pohlman, Moventas
	The “GRC1.5”: Up-Tower Gearbox Testing to Investigate Bearing Axial Cracking	Jonathan Keller, NREL, and David Vaes, SKF
Tribology and Failure Modes Plenary Session		
10:45 a.m.	Benchtop Testing to Investigate Bearing Axial Cracking	Aaron Greco, Argonne
	Surface Engineering and Coatings	Gary Doll, University of Akron
	Rolling Contact Fatigue Modeling Considering Materials and Lubrication	Nathan Bolander, Sentient Science
Breakout Sessions: Gap Identification and Characterization		
1:00 p.m.	Design, Testing, and Analysis Operation and Maintenance, Monitoring, and Data Tribology, Lubricants, and Failure Modes	

Time	Topic	Speaker and Affiliation
Operation and Maintenance, Monitoring, and Data Plenary Session		
8:30 a.m.	Database, Operation and Maintenance, and Condition Monitoring Update	Shawn Sheng, NREL
	The Role of Condition Monitoring in Operation and Maintenance	AnneMarie Graves, Vestas Upwind Solutions
	Failure Forecasting	Ryan O’Connor, EDF Renewables
Data-Driven Reliability Plenary Session		
10:15 a.m.	Data Analytics Potential and Promising Developments	Jason Cotrell, NREL
	Data Analytics for Wind Power Plant Monitoring	Jan Helsen, OWI-Lab
	Big Data, Analytics, and the Cloud: Trends and Challenges in the Industrial Internet	Bouchra Bouqata, GE
	A Physics-Based Prognostics and Diagnostic Solution for Gas Turbine Life-Cycle Management	Ashok Koul, Life Prediction Technologies Inc.
Breakout Sessions: Recommendations and Summaries		
12:30 p.m.	Design, Testing, and Analysis Operation and Maintenance, Monitoring, and Data Tribology, Lubricants, and Failure Modes	

Plenary Presentation Overview

This section summarizes each of the presentations in the plenary sessions. The majority of these presentations are available at http://www.nrel.gov/wind/grc/meeting_drc_2016.html.

Design, Testing, and Analysis

Closing the Gap between Design and Operational Requirements in Gearbox Engineering

Zhiwei Zhang, Romax Technology

The wind industry is being challenged by multiple failures in gearbox and bearing design. A variety of modeling and simulation techniques can be used to improve design practices and increase gearbox reliability. The GRC gearbox #3 design, build, and testing project was used as an example of this process. Shortcomings in the design of the previous version of the gearbox were discovered through the testing and modeling process and then corrected through a redesign to improve planetary section load sharing, lubrication, and durability.

Toward Higher Gearbox Reliability and Torque Density

Jon Pohlman, Moventas

New technologies, such as surface finish and hardening improvements; new planetary arrangements; and journal bearings have the potential to increase the reliability and torque density of wind turbine gearboxes. Some of these technologies have been implemented in reengineering gearboxes for existing turbines, such as the Moventas 1.5XL gearbox. Design features of that reengineered gearbox were presented and related to current design deficiencies.

The "GRC1.5": Up-Tower Gearbox Testing to Investigate Bearing Axial Cracking

Jonathan Keller, NREL, and David Vaes, SKF

Bearing axial cracking has contributed to a significant number of premature failures in wind turbine gearbox intermediate and high-speed shaft bearings. This presentation discussed the testing planned on a commercial gearbox in the DOE-owned GE 1.5 SLE turbine at the National Wind Technology Center. The test program focuses on measuring the operational environment of the high-speed shaft cylindrical roller bearings—loads, speeds, and other tribological factors such as temperature, water, humidity and stray current. Of particular interest is the measurement of the slide-to-roll ratio of the rollers, which will be measured though a patented SKF technique. In conjunction with knowledge of the sliding in the bearings, advanced finite element analyses will project roller contact stresses. The environmental conditions, turbine operating modes, and grid conditions will be matched with the measurements to correlate conditions that have been found to result in WECs in the Argonne benchtop test rigs.

Tribology and Failure Modes

Benchtop Testing to Investigate Bearing Axial Cracking

Aaron Greco, Argonne National Laboratory

Premature bearing failures referred to as axial cracks or WECs manifest as subsurface crack networks associated with microstructural alteration to the steel. Argonne is leading DOE's tribological investigation of these failures through in-depth characterizations of failed wind turbine bearings and the development of benchtop test methodologies to replicate the failures. Using advanced synchrotron X-ray tomography, bearing samples were scanned and cracks were mapped and characterized. Additionally, a benchtop test methodology was successfully developed to generate WECs, and a parametric study was conducted to determine the influence of load, slide-to-roll ratio, and lubrication condition on the formation of WECs. The initiation of the WEC failure was observed and characterized in four characteristic steps, which shows the crack forming before the white etching microstructural alteration. This finding suggests that the white etching microstructure alteration is not necessarily the cause of the failure but the result of premature crack initiation. This ongoing work aims to characterize the various pathways to this premature bearing failure, including the loading conditions, lubricant effects, and other system drivers such as stray electrical currents.

Surface Engineering and Coatings

Gary Doll, University of Akron

Some wind turbine bearings are not achieving their desired operational lives because of life-limiting wear modes. Tribological issues manifest through different bearing failure modes in various systems of wind turbines. The primary mechanisms in pitch/yaw bearings, main shaft bearings, the gearbox, and the generator are fretting/false brinelling, scuffing/smearing, micropitting, and WECs. Each failure mode was summarized, along with how they can be mitigated by surface engineering solutions.

Rolling Contact Fatigue Modeling Considering Materials and Lubrication

Nathan Bolander, Sentient Science

Computational simulations have been developed to predict rolling contact fatigue, accounting for parameters such as system loading, material microstructure, and lubrication conditions. System-level loading analysis is used to calculate the bulk loading at the contact surface of the bearings and gear teeth. The material properties (microstructure, residual stress, surface roughness, and so on) of the contacting component can be incorporated into the model, and the material response to cyclic loading can be calculated. Further, the lubrication condition at the contacting surface can be calculated with elasto-hydrodynamic lubrication simulations, based on the operating conditions and the lubricant and surface properties, to resolve the local asperity contact pressure and surface traction. Together these computational simulations are used to calculate a statistical probability of component life and failure modes. An example was presented wherein the Sentient simulation tool was used in wind turbine gear application to calculate a relative statistical life prediction of varying material quality grades; another example was presented for a rotorcraft gear application wherein a similar prediction was calculated accounting for surface finish, residual material stress, and material quality.

Operation and Maintenance, Monitoring, and Data

Database, Operation and Maintenance, and Condition Monitoring Update

Shuangwen Sheng, NREL

New statistics indicate that gearbox reliability is still a challenge faced by the industry despite improvements in recent years. The gearbox reliability database continues to attract more participation and data submissions. The latest damage distribution shows that bearings account for 76% of damage, gears for 17%, and housing and lubrication systems for 7%. A web interface is being developed to provide a centralized location for data exchange and reporting. Two big challenges faced by the database effort are standardized terminologies and active data submission by partners.

The needs and opportunities for research to help the industry improve O&M practices and reduce the cost of energy were also presented. Relative to data analysis, the industry has (to date) focused on performance monitoring and condition monitoring for component reliability improvement. A prognostics and health management framework has been applied successfully in other mature applications and has the potential to benefit the wind industry.

Vibration-based condition monitoring has also been shown to have additional benefits to product design due to its capturing of high-frequency vibration data. Compact filter testing and analysis is expected to result in a cost-effective condition monitoring solution for the wind industry. Oil cleanliness-level measurements provide further evidence of the potential damage from transient events to wind turbine gearboxes. Gear failure detection based on SCADA analysis has shown the opportunity and potential of data mining. Remaining useful life (RUL) prediction based on SCADA system and other data, using big data analytics and physics-based modeling approaches, will be the new focus of work in the wind power plant O&M area.

The Role of Condition Monitoring in Operation and Maintenance

AnneMarie Graves, Vestas Upwind Solutions

The role of condition monitoring in wind power plant O&M was discussed. Historical data has shown that major components account for 60%–70% of a wind turbine’s operating costs. The goal of condition monitoring is to help reduce the likelihood of major component failures and their replacement costs. Various condition monitoring tools are available, including SCADA data mining, vibration analysis, borescope inspections, and oil sampling. To reap the benefits of condition monitoring, a proactive operations culture with RUL predictions and analytics is needed. Currently, most condition monitoring techniques can provide only 1 year of failure prediction. Future research efforts should focus on predicting failures before the failure mode has occurred fleetwide and providing 1–3 years of prediction before the failure occurs. For failure prediction based on either statistical methods or physics-based models, the specific failure mode needs to be known. The accuracy of estimated life span impacts project operating budgets.

Failure Forecasting and Life Data Analysis

Ryan O'Connor, EDF Renewables

Failure foresting can be conducted during the project development phase and the generation and operation phase. The forecasts of the former can be on major component repairs; the forecasts of the latter can benefit annual operational budgets and maintenance plans. Typically, failure forecasting involves the three steps of data collection, model development, and running the forecast. Two examples were given: one on gearbox failures to support spare gearbox reservation and the other on pitch bearing failures to support inspection planning. Highlights from the first example include reliability data needs to include information on not only replacements but also out-of-service gearboxes and faults. Data validation is important and time-consuming, and reliability models need to be built according to specific gearbox models. The reliability models were built by using a maximum-likelihood method based on three assumed initial distributions and choosing the one that led to the greatest sum of maximum log-likelihood values. Estimations of the number of gearbox failures during the period of interest were obtained based on the reliability models established for each gearbox model at the plant. The second example used a risk-based approach to evaluate the inspection interval for pitch bearings. In addition to the pitch bearing reliability model, a few other inputs were used, such as the inspection cost, fault detectability, planned replacement cost, and catastrophic event cost. The examples demonstrated that failure forecasting and lifetime data analysis can help improve wind power plant O&M.

Data-Driven Reliability

Data Analytics Potential and Promising Developments

Jason Cotrell, NREL

Different parties may have different interpretations of the meaning of big data analytics. Data analytics typically involve storage, access, visualization, and prediction implemented using various algorithms such as machine learning. The ongoing data revolution is not in the amount of data available but rather the new and evolving tools for data analysis available to everyone. For the wind industry, data analytics can benefit not only reliability but also performance and grid integration, leading to reduced cost of energy. It is likely that future decision-making at almost every level can be based on data, from physical measurements on turbines or the balance of plant to maintenance, logistic, and operation decisions. To make big data analytics more beneficial to the wind industry, it is necessary to identify problems and opportunities, conduct the needed basic research, and validate the proper tools and approach to solve these problems. The advancement of data analytics for the wind industry needs involvement from all parties, including industry, academia, and government.

Data Analytics for Wind

Jan Helsen, OWI-Lab

To make offshore wind competitive during the next 10 years, the levelized cost of energy must be reduced. This can be accomplished by looking at both capital and operating expenses. Experience in other industries has shown the importance of understanding the behavior of the assets, predicting their future responses, and turning data into knowledge; and the same applies to the wind industry. Data analytics can help reduce the operating expenses of offshore wind turbines through failure detection, tracking, understanding, and prevention. It can also help improve future product design using field data. A typical wind power plant generates various types of data in large volumes and varieties that can be handled through a big data storage platform. Standard SCADA data is not sufficient for turbine component lifetime assessments; instead, high-frequency time-series measurements are needed, especially to capture detailed short-duration events and the load history experienced by a turbine. Wind power plant data analytics can bring additional insights and potentially help controller optimization because decisions made based on individual turbines may not always be optimal. For SCADA data-based condition monitoring, the limitation of absolute alarms can be overcome by advanced data analytics applied on both time-series data and turbine status codes. It is important to combine various data sources to understand failures.

Big Data, Analytics, and the Cloud: Trends and Challenges in the Industrial Internet

Bouchra Bouqata, GE

When more than 50 billion machines in almost all industrial applications are connected through the industrial internet, the data must be appropriately handled. For example, the data generation rate is at approximately 588 gigabytes per day for the monitoring of gas turbine compressor blades alone. The potential data volume generated by gas turbines is approximately 7 times greater than social media, and it is a big data challenge. The wind industry faces a similar challenge when all turbines are connected because each turbine generates approximately 100 parameters at 10-minute intervals. Opportunities exist for the wind industry to explore big data technologies to benefit prognostics, asset productivity, and system optimization. A solution for the wind industry and the broader industrial internet requires contributions from all parties ranging from big data analytics, cloud computing, mobile access, end-to-end security, a consistent and useful user experience, a scalable environment for development and deployment, and integrated asset data management using the cloud. There are many challenges, such as the integration of a large volume and variety of data to find new insights, bridging data-driven and domain-based analytics, security, and infrastructure.

A Material Physics-Based Prognostics and Diagnostic Solution for Gas Turbine Life-Cycle Management

Jun Zhao and Ashok Koul, Life Prediction Technologies Inc.

A material physics-based diagnostics and prognostics and health management framework for gas turbines was presented. It has eight layers, ranging from an in-service prognosis engine, to transfer functions between cracks and performances as well as symptoms picked up by dedicated sensors, to reasoning and real-time correlation. The framework incorporates both diagnostics and prognostics in a hybrid manner. Typical damage modes in gas turbine engines were then highlighted, followed by assumptions and definitions in material physics-based life prediction. An industrial turbine heat transfer model using computational fluid dynamics and finite element analysis was discussed. Gear failure modes that may be seen in wind turbines were discussed as an example to which the presented gas turbine framework can be extended. A conceptual framework for the wind turbine application was provided by highlighting the needs of structural analysis, correlation between diagnostics and prognostics, and metallurgy.

Breakout Session Overview

This section serves as a summary of the breakout sessions in each of the technology areas. As indicated in Table 1, the afternoon of each day was devoted to these breakouts. Within each breakout session, attendees gathered in groups of four to six to facilitate more interactive discussions. On the afternoon of the first day, group members discussed the gaps in each technology area among themselves prior to briefing the entire group in order of importance. On the afternoon of the second day, the groups outlined a plan of action for the most important gaps. This section of the report summarizes the gap identification and plan of action.

Design, Testing, and Analysis

Approximately 25 individuals attended the design, testing, and analysis breakout session, and they identified 12 challenges related to drivetrain reliability. These challenges can be roughly grouped into three areas: the physics of failure for uncharacterized failure modes, evaluating the risk of new technologies, and challenges for standards and certification methodologies.

Uncharacterized Failure Modes

It has been observed that the most prevalent failure modes in wind turbine drivetrains are not accounted for in current design standards and are poorly understood. Bearing failures and their underlying physics remain a top research priority within the industry. Examples of such failure modes are main bearing failures through micropitting, WECs in gearbox bearings, and generator bearing failures. Design standards are well developed for the rolling contact fatigue failure mode but not these failure modes. Because the failure modes are not well understood, the mitigation strategies being developed and fielded may only partially address the failure and can take years to assess.

The group expressed support for current research into WECs. Although they occur frequently in intermediate and high-speed section bearings, typically they can be repaired quickly up-tower. The group also emphasized the importance of continued R&D for main bearing failures, including full-scale measurements and modeling. In particular, axial motion of the main bearing races relative to one another and ideally of the rollers themselves was of interest. Additionally, stray current measurements are also of interest. Some generator bearing failures are still not well understood. The R&D community can also investigate which operational conditions and loads correlate to the failure modes observed in operation. With this information, the highest risk operational conditions could be quantified using turbine SCADA data, high-fidelity models, or some combination of the two. Once the physics of failure is better understood in each case, the R&D community should participate with industry in transitioning this knowledge to the common design methods, modeling tools, and eventually design standards. At the same time, the R&D community can participate in developing guidelines for the validations of proposed mitigation methods through testing.

Evaluating Risk of New Technologies

Although the wind industry is maturing, new technologies are constantly entering the marketplace. Slowing the pace of technology adoption, however, are concerns by financiers, developers, and operators about the long-term reliability of these technologies. One example about which these groups are concerned is large, direct-drive drivetrains typically in offshore wind power plants. Methodologies to evaluate the technical risks of new drivetrain technologies related to performance and reliability would be effective in addressing perceptions of scaling and certification risks.

Standards and Certification

In terms of component standards and certification requirements, several challenges and shortcomings were identified. Although most do not have an R&D component, they are described here for completeness.

Existing design standards are largely tailored to a 20-year life span; however, in some markets and applications, a reduced design life may be acceptable and lead to components with lower capital costs. Similarly, the life-span calculations in the design standards should be tailored to account for components that can be serviced up-tower, which is becoming more common. The testing requirements in the design standards can certainly be improved. For example, they could be changed to correlate to the failures that are commonly observed in operation rather than a highly accelerated lift test. The main interest would be to improve testing capabilities that shorten the certification cycle. In the area of certifications, certifying the components in the aftermarket was observed as an issue. Some rebuild shops make changes to the original design to "upgrade" the reliability of the component, but there is no consensus on the means to evaluate these changes.

Tribology and Failure Modes

Approximately 40 attendees participated in the tribology breakout session. This group's discussion focused on the tribological failures and the material and lubrication factors in wind turbine drivetrain reliability. They identified critical issues in these areas, and they discussed potential opportunities for focused R&D efforts. The topics identified can be categorized in two areas: identification and characterization of contact failures and aspects of lubrication, coatings, and surface treatments.

Identification and Characterization of Contact Failures

Many failures that impact the reliability of drivetrains and other mechanical systems in wind turbines initiate at the contacting surfaces of the bearing and gear components, including the gearbox, main bearing, generator bearings and brushes, and actuator systems for blade pitch and nacelle yaw control. These components suffer from premature cracking (e.g., WECs), pitting, scuffing, micropitting, false brinelling, and wear. The transient and largely unpredictable operation of these systems contributes to a challenging environment leading to these failures. Additionally, determining the root causes and selecting appropriate mitigation approaches is difficult given the complexity of the factors influencing the contact conditions. In common with the session on design, testing, and analysis, a number of tribological failures currently impacting drivetrain reliability were identified, with WECs and main bearing failures being the most critical.

WECs remain a leading mode of failure in gearbox bearings, and the group discussed that there is limited understanding about the root causes of these failures and a lack of appropriate testing to validate potential mitigation approaches. This may be because of a lack of understanding about the physical cause of the premature cracking and the influence of various operational conditions, bearing materials, lubricants, and coatings. Specifically, there is a need to better understand the influence of black-oxide treatments and their long-term effectiveness and a need for more failure analysis of black-oxide-treated bearings from the field. The influence of lubricant-additive chemistry on preventing or promoting WECs was also discussed, focusing on the influence of metallic versus ashless additives and water contamination. Additionally, the role of bearing materials was discussed, specifically the potential benefits of case carburized alloys and how these benefits can be confirmed through benchtop testing. In general, the group agreed that there is a critical need to develop benchtop testing methodology to test the influence of these operational conditions and material/lubricant factors; further, a standard test that is capable of evaluating the potential benefit of various mitigation approaches, preferably at a full-scale bearing level, is needed. The participants gave support to DOE's current R&D efforts on WEC failure investigations and recognized the value that the recent developments in benchtop testing have provided. They recommended continuing with the current project plan in addition to increasing the focus on addressing the issues mentioned above and developing a full-scale bearing test rig to evaluate WEC failure.

The other critical drivetrain component failure identified by the group is the main shaft bearing. According to the participants, main bearing failures are becoming a critical issue, and the cost of replacement is an increasing concern to the industry. It is not clear if there is a common mode of failure for main bearings; however, based on many accounts, failures initiate as micropitting, adhesive wear or false brinelling. Although each of these failure modes is fundamentally different, both are the result of sliding at the contact where the surfaces have inadequate lubricant film separation and the asperities are in contact. Additionally, standstill corrosion appears to be another failure mode common in some main bearings. Although some of the sliding can be minimized through bearing design, the influence that sliding has on the contact can be addressed through grease and surface treatments and coatings. The participants highlighted issues with grease lubrication of the main bearing, specifically the type of grease, application, retention, and maintenance. Issues were raised regarding the testing methods used to evaluate greases for wind turbine main shaft bearings and a need for more appropriate methods for this application. Additionally, the need for further research efforts to evaluate the benefits of coatings for main bearings was discussed, specifically diamondlike carbon coatings.

Lubrication, Coatings, and Surface Treatments

Additional discussions in this breakout group can be categorized under the general topic of lubrication, coatings, and surface treatments. In addition to how these topics relate to the specific failure modes described in the previous section, there was general concern regarding lubricant, coating, and material choices for the entire turbine drivetrain and other mechanical systems. There were overall questions regarding the performance benefits these choices present and a desire for validating them through more appropriate testing methodologies. Further, there is a lack of fundamental knowledge about how specific materials, "designer" coatings, and treatments interact with certain lubricant additive chemistries; therefore, the lubricant and materials cannot be considered separately but rather in combination as a complete system. This presents additional R&D challenges that require further investigation.

On the topic of lubrication, there was discussion about determining the drain interval that would maximize the life of the gear oil and greases or development of new lubricants that enable longer drain intervals. This was particularly a topic of interest with regard to offshore turbines, for which the cost of maintenance is considerably higher than land-based turbines. The topic of water contamination in oil was also discussed, specifically regarding the interaction of water with certain metal-containing additive chemistries. Additionally, the participants expressed a need for R&D to develop new greases for wind turbine applications that provide better performance at a cost that is practical for the industry. Another point made on the topic of lubrication is that the standardized test used to certify gear oil or grease is not a good representation of how the product performs in the field; therefore, there is a need for better benchtop test methodologies to evaluate the performance in conditions that are more relevant to wind turbine conditions.

One observation on the topic of coatings and surface treatments is that there is general confusion about the differences between the two. Surface treatments generally refer to black-oxide treatments, and coatings commonly refer to diamondlike carbon coatings. Black-oxide is a conversion layer used mainly to protect against corrosion, but it has been shown to have some tribological benefits; however, the black-oxide layers are relatively soft and readily removed in sliding contact. On the other hand, a diamondlike carbon coating is applied to the surface of the component primarily to provide wear protection given its high-hardness properties. In addition to these general differences, there is still some fundamental lack of understanding regarding how both surface treatments and coatings perform in certain conditions and how they interact with certain lubricant additive chemistries.

Operation and Maintenance, Monitoring, and Data

Approximately 45 individuals attended the O&M, monitoring, and data breakout session. The group identified approximately three dozen challenges, which can be roughly grouped into the following areas: O&M, databases and data management, condition monitoring, and standards. One common objective of these areas is to reduce the high variability in component life.

The most problematic components identified by the group—listed generally in order of importance—are gearboxes, main shaft bearings, blades, generators, transformers, and pitch bearings. The group nearly unanimously identified the reliability of the main shaft bearings as the second most important reliability challenge, after gearbox reliability. An R&D effort that includes testing, modeling, O&M, failure analysis, materials, and tribological factors would help address stakeholder concerns with main bearings. The group was also interested in the effectiveness of different maintenance and repair practices, such as comparing the effectiveness of up-tower and down-tower maintenance and repair services.

With the emergence of new technologies and the industrial internet, a challenge is to bring wind turbines and the balance of plant into the age of the industrial internet. One example would be the development and adoption of new sensors that may make traditional manual oil sampling unnecessary.

Operation and Maintenance

More accurate RUL estimation of wind turbine components is needed to reduce wind power plant O&M costs. The development of accurate and long-term RUL estimation methods will also provide needed inputs to implement advanced algorithms that improve plant performance and reliability.

Workshop presenters described the combination of data-driven and physics-based methods as a promising approach to accomplish these goals. Data-driven methods rely on mining or analyzing data from monitored turbines. Examples of data-driven methods include SCADA data mining and analysis for the diagnosis of incipient failures in blade pitch bearings, hydraulics, and electric systems and the correlation of high-torque events with gearbox failures.

Physics-based models are developed based on an understanding of turbine component loads and theoretical or empirical failure progression principles, such as fracture mechanics. These models capture underlying dominant principles for certain input-output relationships, such as component crack or life change with load. Data-driven and physics-based approaches are complementary, and each can be used to "fill in" for the other—for example, when insufficient data exists for data-driven models or when the physics are unknown or too difficult to model for physics-based models.

The group also identified tailored (i.e., varying sampling rates for different types of measurements) or increased SCADA sampling rates (e.g., from 10-minute to 1-minute) as one way to improve failure forecasting and estimations of RUL.

Databases and Data Management

The current gearbox reliability database managed by NREL is highly valued by the breakout session attendees. Several attendees emphasized the importance of expanding the database in both depth and scope. Specifically, information to relate failures to turbine age, gearbox architecture, and wind site and grid connection characteristics would be valuable to support failure forecasting.

In general, the wind industry has not been very open regarding data sharing [37]. DOE and its laboratories are considered an objective third party well positioned to host industrywide data and help coordinate with other data collection efforts in the United States, such as the Generating Availability Data System mandated by the North American Electric Reliability Corporation and benchmarking data collection by the Utility Variable-Generation Integration Group, to avoid duplicative efforts. Attendees also recommended that the United States consider leveraging data collected and data management systems developed in Europe through international collaborative agreements.

Different data collection practices are employed across the industry. The variation and challenge in accommodating human factors and behaviors were also cited as substantial undertakings. The attendees advocated the need for a common data collection tool using consistent terminology and a format for unstructured data. SCADA, condition monitoring, and other data streams could be integrated smoothly with computerized maintenance management systems to facilitate analysis. Given the vast amount and diverse types of data being generated at a typical wind power plant, some enhanced infrastructure for data collection and storage can make data-enabled reliability possible based on real-time data collection, complex data analysis, and tailored decision support.

Condition Monitoring

During the past few years, the U.S. wind industry has witnessed the transition of condition monitoring from small exploratory efforts to a widely recognized technology that can improve O&M practices and reduce the cost of wind energy. One example of this transition is the common deployment of at least one condition monitoring technology for new wind power plants. One benefit that the industry has experienced is to help convert a potential gearbox replacement to an up-tower repair due to early detection of the inherent damage prior to collateral damage occurring. Despite these developments, there remains an industrywide interest in a large-scale cost-benefit analysis of condition monitoring that might be best suited as a joint-industry effort. This would take the form of a full wind power plant deployment and the evaluation of various condition monitoring technologies, with support from condition monitoring equipment suppliers, along with sharing the results with the wider industry.

Although these developments are very exciting, the group identified some areas of work with R&D elements as valuable, such as testing to support the development of novel condition monitoring technologies and estimations of RUL that can relate typical environmental, load, and condition monitoring measurements with the component physical condition throughout the progression of damage. High-value examples include main and gearbox planetary stage bearings and vibration, oil particle count, and oil or grease quality measurements. In terms of sensor technology, sensors to detect cracking of gear teeth, bearing raceways, gearbox housings, or other structural elements would be valuable; along with means to determine optimal sensor locations. When root cause analysis is conducted for certain failures, feedback to the design process for product improvements can be provided.

Standards

The group identified a need for new standards, best practices, procedures, and methods for data collection, data analysis, and O&M—such as turbine shutdown operations to mitigate extreme loads—through closer interactions with the American Wind Energy Association, International Electrotechnical Commission, International Energy Agency, the Utility Variable-Generation Integration Group, and other appropriate standard committees.

Summary and Recommendations for Future R&D Activities

The cost of energy from wind has declined tremendously during the past two decades but not without significant industrywide effort and resources. Wind power plant owners and operators report that O&M costs in existing wind power plants are higher than anticipated and to the point that they can even slow the development of new wind power plants. A major portion of these costs are related to drivetrain reliability. Increasing drivetrain reliability would significantly benefit the wind industry, but the predominant drivetrain component failure modes are not simple in nature, accounted for in design standards, typically related to quality control, or generally attributable to specific component suppliers.

Opportunities for improving drivetrain reliability exist across the spectrum, ranging from developing new wind turbine technologies to optimizing O&M procedures. For example, turbine and drivetrain technologies such as new materials and coating, reengineered components, and turbine controller and power converter software can increase component reliability. Improved O&M procedures that use advanced diagnostics, prognostics, and O&M modeling tools can reduce O&M effort and costs while maintaining high availability. These reliability improvements will improve wind power plant profitability, helping achieve U.S. wind deployment goals.

Participants at the Wind Turbine Drivetrain Reliability Collaborative Workshop discussed the state of the art in wind turbine drivetrain mechanical system reliability as well as R&D challenges that, if solved, could reduce O&M costs and benefit the U.S. land-based and offshore wind industries. The R&D challenges were examined in breakout sessions in the areas of drivetrain design, testing, and analysis; tribology and failure modes; and O&M, monitoring, and data. Below is a summary of the key R&D challenges:

- Characterize and develop life-span methods for gearbox WEC and main bearing failure modes. These failure modes are not well understood, occur far earlier than the predicted design life, have no life-span methodology or proven mitigation method, and account for many expensive failures of gearbox bearings and main bearings. Reducing gearbox failures and main bearing failures will reduce wind power plant O&M costs by increasing inherent drivetrain reliability.
  - For the WEC failure mode, continue the current research program consisting of the following steps:
    - Determine the physical mechanisms at the material level that lead to premature cracking.
    - Further develop a benchtop testing methodology to replicate WECs, and develop a full-scale bearing test rig that can be used to validate approaches to mitigate the failure.
    - Conduct testing in a wind turbine to understand the operational conditions conducive to WEC formation.
    - Assess the operational conditions that are most conducive to WEC formation as determined by material and benchtop testing, and make recommendations for mitigation solutions.

- For main shaft bearing failures:
  - Conduct a full analysis to determine the most prevalent root causes.
  - Develop or identify tests that accurately represent the contact conditions and can be used to evaluate existing greases and coatings or develop new ones.
  - Model and conduct testing in a wind turbine to understand the operational conditions conducive to the propagation of damage identified in the failure analysis.
- Develop a method to systematically evaluate the risk of new technologies. A perception of increased risk can slow the adoption of potentially viable technology and also increase the cost of implementing it.
- Develop and demonstrate approaches for combining data-driven and physics-based models to increase the accuracy of remaining useful life predictions and account for the dominant wind turbine component failure modes.
- Develop novel condition monitoring technologies and methods to support estimations of component RUL through tests that relate typical environment, load, and condition monitoring measurements with the component physical condition throughout the progression of damage. Ideally, this would include the collection and release of the testing data to the industry.
- Increase the depth and breadth of the current drivetrain reliability database. Leverage data collected and data management systems developed in Europe using international collaborative agreements. Link the additional data and failures to identify possible root causes or failure precursors. This linkage will improve operations and support future product development. Tools developed and experience accumulated in drivetrains can be expanded to other major turbine subsystems and components.

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