Insights on Wind Turbine Maintenance From the Usage History of a General Electric Transportation Systems Gearbox

Jonathan Keller, Syenna Graham, and Yi Guo

National Renewable Energy Laboratory

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

This report is available at no cost from the National Renewable Energy Laboratory (NREL) at www.nrel.gov/publications.

Contract No. DE-AC36-08GO28308

Technical Report
NREL/TP-5000-82704
July 2022

Insights on Wind Turbine Maintenance From the Usage History of a General Electric Transportation Systems Gearbox

Jonathan Keller, Syenna Graham, and Yi Guo

National Renewable Energy Laboratory

Suggested Citation
Keller, Jonathan, Syenna Graham, and Yi Guo. 2022. *Insights on Wind Turbine Maintenance From the Usage History of a General Electric Transportation Systems Gearbox*. Golden, CO: National Renewable Energy Laboratory. NREL/TP-5000-82704. https://www.nrel.gov/docs/fy22osti/82704.pdf.

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

This report is available at no cost from the National Renewable Energy Laboratory (NREL) at www.nrel.gov/publications.

Contract No. DE-AC36-08GO28308

Technical Report
NREL/TP-5000-82704
July 2022

National Renewable Energy Laboratory
15013 Denver West Parkway
Golden, CO 80401
303-275-3000 • www.nrel.gov

NOTICE

This work was authored 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 the U.S. Department of Energy Office of Energy Efficiency and Renewable Energy Wind Energy Technologies Office. The views expressed herein do not necessarily represent the views of the DOE or the U.S. Government.

Cover Photos by Dennis Schroeder: (clockwise, left to right) NREL 51934, NREL 45897, NREL 42160, NREL 45891, NREL 48097, NREL 46526.

NREL prints on paper that contains recycled content.

Acknowledgments

This work was authored by the National Renewable Energy Laboratory, operated by Alliance for Sustainable Energy, LLC, under Contract No. DE-AC36-08GO28308 for the U.S. Department of Energy. Funding provided by the U.S. Department of Energy Office of Energy Efficiency and Renewable Energy Wind Energy Technologies Office. The authors would like to thank Shawn Sheng, Scott Lambert, and Roger Bergua Archeli of the National Renewable Energy Laboratory for their assistance.

List of Acronyms

GE	General Electric
GETS	General Electric Transportation Systems
Hz	hertz
IEC	International Electrotechnical Commission
ISO	International Organization for Standardization
kN·m	kilonewton meter
kW	kilowatt
kWh	kilowatt-hour
m	meter
mg	milligram
mm	millimeter
NREL	National Renewable Energy Laboratory
O&M	operations and maintenance
ppm	parts per million
rpm	revolutions per minute
s	second
SCADA	supervisory control and data acquisition
TR	technical record
TS	technical specification

Table of Contents

List of Figures

List of Tables

1 Introduction

Wind power plant operational expenditures remain an appreciable contributor to the overall cost of wind energy, even for newer land-based wind plants (Wiser, Bolinger, and Lantz 2019), and are estimated to be even higher offshore (Stehly, Beiter, and Duffy 2020), accounting for 25% to more than 35% of the levelized cost of energy (Lantz 2013; Carroll et al. 2017; Wiser, Bolinger, and Lantz 2019). Approximately half of land-based plant operational expenditures are associated directly with turbine operations and maintenance (O&M) (Lantz 2013; Wiser, Bolinger, and Lantz 2019), including a significant percentage from premature gearbox failures (Wiser, Bolinger, and Lantz 2019). More reliable components and better O&M strategies have the potential to reduce the levelized cost of energy by 10% or more for land-based wind plants (Wiser, Bolinger, and Lantz 2019; Stehly, Beiter, and Duffy 2020) and could have an even greater impact on fixed-bottom, offshore wind plants (Stehly, Beiter, and Duffy 2020).

Although damage to the gears occurs less frequently than damage to the bearings in wind turbine gearboxes (Sheng 2017), gear damage still presents a reliability challenge. Micropitting is a form of hertzian fatigue damage that occurs on gear teeth. It appears as ultrafine cracks on the surface of the flank, with the resulting loss of material looking like gray staining. Although the cause of micropitting is not fully understood, it appears to result from cyclic stresses and plastic deformation on the asperity scale. In addition, sliding between gear teeth causes traction forces that subject asperities to shear stress. Micropitting is influenced by a number of factors, including loads, speeds, temperatures, gear tooth macro- and micro-geometry, flank surface finish, heat treat, and lubricant properties. Micropitting can lead to significant surface damage, macropitting, and catastrophic failure. Alternatively, micropitting may appear in patches and be arrested as tribological conditions improve during run-in. When designing gearing for critical applications, it is desirable to calculate the risk of micropitting in an effort to avoid it. However, currently there is no comprehensive model to predict micropitting risk (Olson, Michaud, and Keller 2020a).

Recently, micropitting that occurred in a wind turbine gearbox (Keller, Michaud, and Lambert 2020) was used as a case study in the International Organization for Standardization (ISO) technical specification (TS) ISO/TS 6336-22 (Olson, Michaud, and Keller 2020a; Olson, Michaud, and Keller 2020b). This specification contains a proposed calculation of risk of micropitting in gear sets in terms of a safety factor based on the ratio of the minimum to the permissible specific lubricant film thickness. The case study only examined the simplified computation in Method B in the technical specification that evaluates points on the path of contact, and micropitting was not predicted to occur (Olson, Michaud, and Keller 2020a). The case study is currently being extended to include the more detailed Method A that evaluates the specific film thickness across the entire contact zone, but more accurate knowledge of the operational history of the gearbox is needed. This report summarizes the operational history of the gearbox.

2 Gearbox Usage History

The U.S. Department of Energy installed a General Electric (GE) 1.5-megawatt wind turbine at its National Wind Technology Center on NREL's Flatirons Campus in Colorado in late 2008. First operations began at the end of September 2009. This turbine is built on the platform of the GE 1.5 SLE commercial wind turbine model (Santos and van Dam 2015). The original gearbox was a GE Transportation Services (GETS) model number 7GA87E2 (Giammarise and Sirak 2009). During the period that the GETS gearbox was installed, a variety of relevant operational data were gathered and are summarized in this section. Maintenance records are reviewed first, followed by two sets of operational data gathered over overlapping periods but at different rates. The first set of data was acquired at a low rate but over the entire installation period, whereas the second set of data was acquired at a much higher rate but only over approximately the last 1.5 years of installation.

2.1 Maintenance Records

The turbine was commissioned at the end of September 2009. Since its commissioning, regular maintenance was conducted by GE and occasional oil samples were collected and analyzed by a third-party laboratory. This information is listed in Appendix A and summarized here.

For the first several years, no anomalies were noted except for one water-content-in-oil reading of 849 parts per million (ppm) in July 2012 at approximately 4,500 hours of operation. It returned to normal levels of 400 to 500 ppm by October, although this is still above the recommended 300 ppm for used polyalphaolefin oil as suggested in International Electrotechnical Commission (IEC) technical report (TR) IEC/TR 61400-4-2 for lubrication of wind turbine gearboxes. Particles were noted in the oil filter in an inspection in January 2015. The first indication of micropitting occurred during a borescope inspection in November 2015 (Keller, Michaud, and Lambert 2020) after approximately 8,000 hours of operation. The micropitting then progressed to the state shown in Figure 1 by the time the gearbox was removed in December 2017 and reinspected. In a period of just over 8 years, records indicate the turbine produced approximately 6 million kilowatt-hours (kWh) of energy in 14,174 hours of grid operation time, representing 8% of the minimum 20-year gearbox design life.

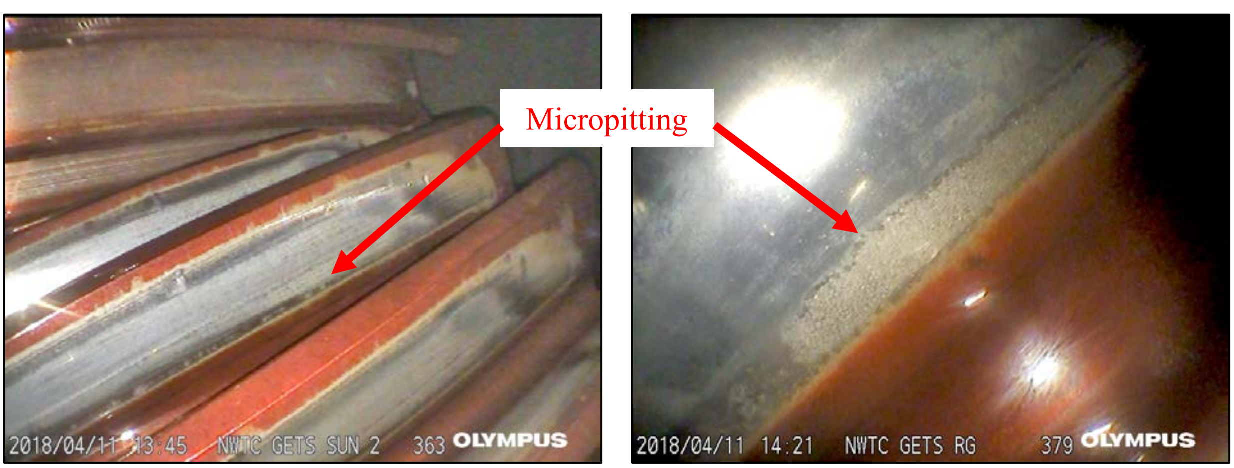

Figure 1. Micropitting of sun pinion teeth in the GETS gearbox

Photos by Scott Eatherton, Wind Driven, NREL 61193 and 61194

The viscosity of the Castrol Optigear A320 oil remained stable from 330 to 310 square millimeters per second (mm^2/s) during the entire installation period, within the range recommended by IEC/TR 61400-4-2 of ±10% of the nominal viscosity of 330 mm^2/s (Castrol 2009). The acid number ranged from 2.35 to the reference value of 3.1 milligrams KOH (potassium hydroxide) per gram, which is also in the recommended range. Oil particle counts ranged from to 20/17/12 early in the gearbox operation to 21/18/14 just prior to removal, which is near the recommendation of -/17/14.

2.2 Analysis of 10-Minute Average Data

NREL has archived records of 10-minute averaged supervisory control and data acquisition (SCADA) system channels from the turbine described in this section. However, the 10-minute records only begin on February 17, 2010, which is approximately 4.5 months after the turbine was first commissioned at the end of September 2009. From the maintenance records in Appendix A, it can be concluded that this data set would at most be missing 845 hours of the full 14,174 hours of operational data. This is the most expansive data set to assess the operational history of the gearbox, although the data represent the conditions averaged over a period of 10 minutes rather than in an instantaneous assessment.

Figure 2 shows the rotor speed and drivetrain torque. Figure 3 shows the rotor speed and electrical power recorded by the turbine. For illustrative purposes, the data are shown on both linear and logarithmic scales. Each point represents the average over 10 minutes. Only conditions in which the turbine is generating power above 10 kW are shown. As described in other publications (Santos and van Dam 2015; Guo and Keller 2020), when the wind speed is less than approximately 5 meters per second (m/s), the turbine operates at a rotor speed of approximately 11 revolutions per minute (rpm) (60% of rated speed). As shown in the figures, at this rotor speed the drivetrain torque is well under 20% of rated torque and the power is less than 150 kW. It is evident from the linear scale plot that this low-speed–low-power condition was the single most common operating condition for the turbine.

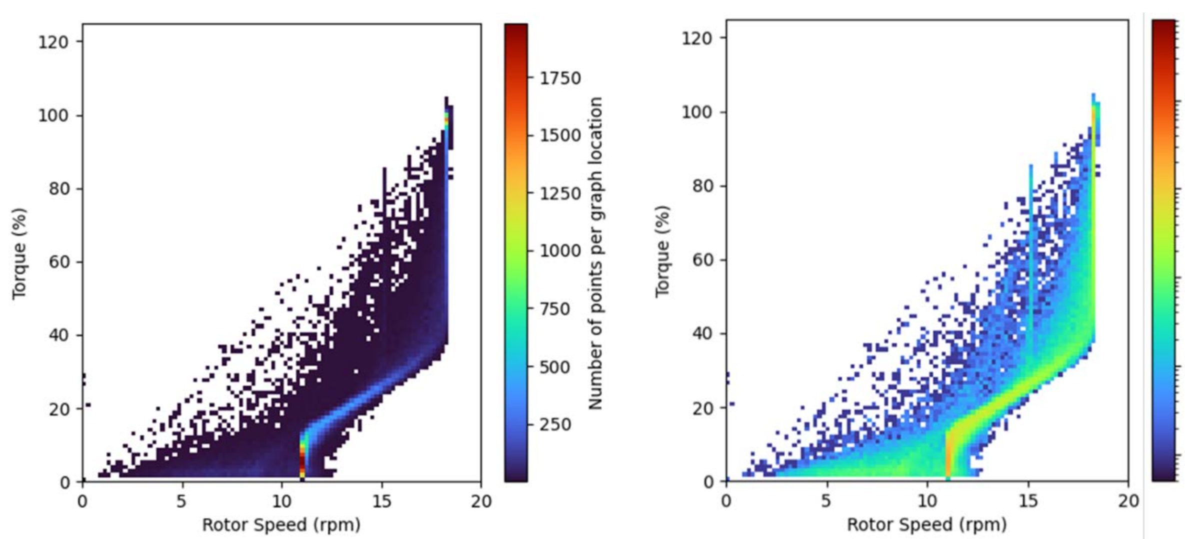

Figure 2. Ten-minute rotor speed and drivetrain torque on linear (left) and logarithmic (right) scales

The next most common condition is when the turbine is operating at the rated rotor speed of 18.3 rpm, which occurs any time the wind speed is above 8 m/s to the cut-out speed of 25 m/s. The torque and active power can vary widely in this condition, ranging from 40% to the rated condition or even slightly above the rated condition. Rated torque and power of 1,500 kW are achieved any time the wind speed is above approximately 11 m/s (Santos and van Dam 2015; Guo and Keller 2020). Aside from these two conditions the turbine primarily operates along its power curve, with points below the power curve likely a result of the presence of transient conditions that vary widely within the 10-minute average.

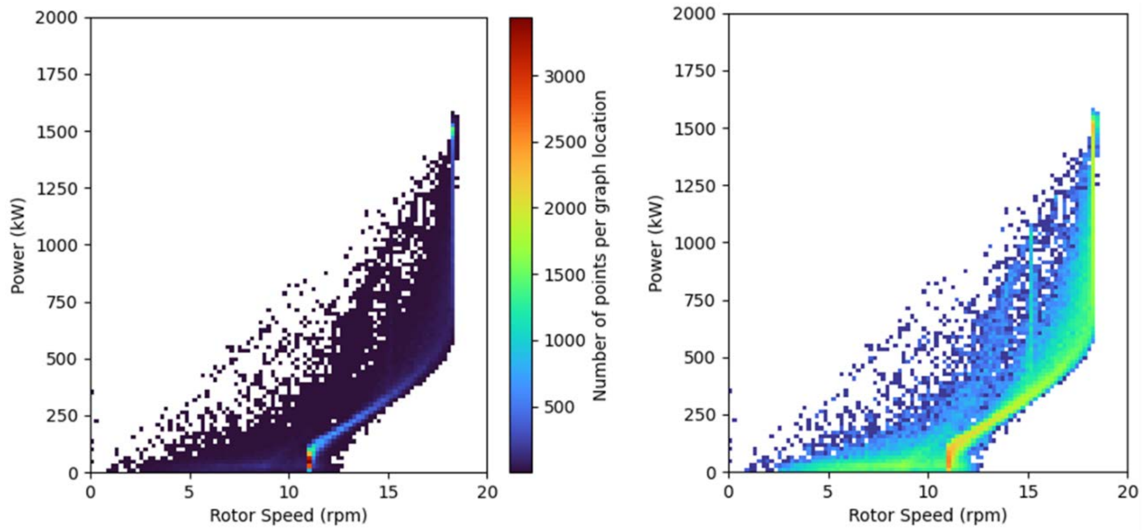

Figure 3. Ten-minute rotor speed and active power on linear (left) and logarithmic (right) scales

Another interesting measurement is the temperature of the oil in the gearbox sump, as shown in Figure 4. The most common condition is approximately 50°C, best observed when viewing on a logarithmic scale. The temperature is rarely above 60°C. There some are conditions in which the oil temperature is below 40°C. In extremely cold conditions it gets as low as 10°C, which most likely occurred during cold start-ups in the winter.

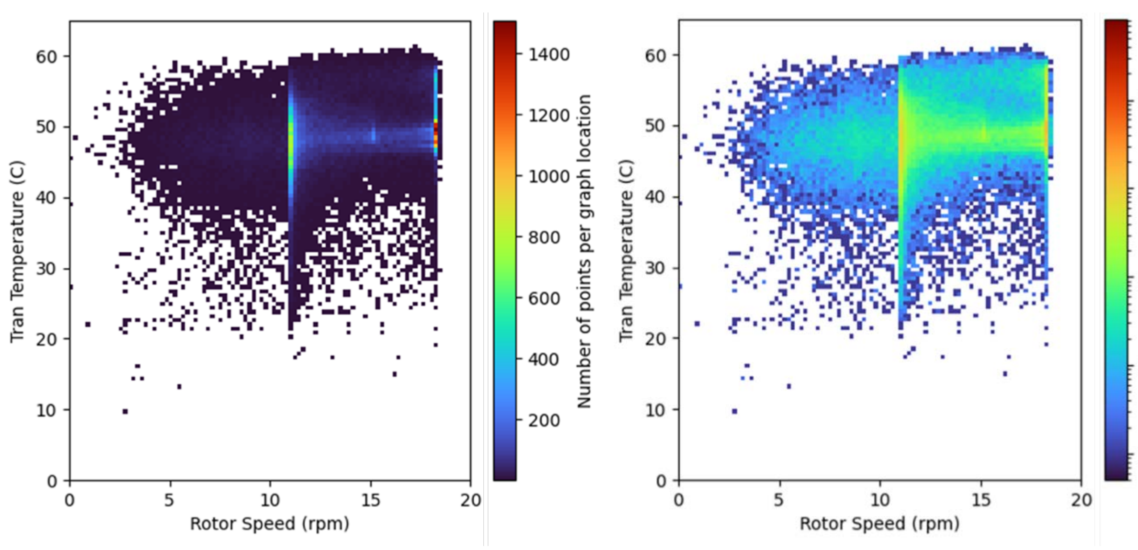

Figure 4. Rotor speed and oil temperature on linear (left) and logarithmic (right) scales

2.3 Analysis of 1-Second Data

In addition to the aforementioned historical 10-minute averaged SCADA data, NREL has more recently acquired select SCADA channels and archived them with additional instrumentation on both a meteorological tower and the wind turbine. These data are typically recorded at rates of 1 hertz (Hz) and 50 Hz (Keller, Guo, and Sethuraman 2019). This section examines 1-Hz data of interest that were gathered from March 22, 2016, through December 2017. These data provide a more accurate representation of the usage of the gearbox compared to the 10-minute averages. The three channels of interest for this period are the measured rotor speed (In_RotorSpd), gearbox output (high-speed) shaft torque calculated by the turbine (AI_CuTorqueAct), and active power (AI_In_GridMonRealPowerAct). The resulting rotor speed–torque curve is shown in Figure 5, and the rotor speed–active power curve is shown in Figure 6. Only conditions in which the turbine is generating power above 10 kW are shown. Gearbox oil temperature data were not available.

Similar to the 10-minute averaged data, the turbine spent most of its time in the low-speed, low-power condition at 11 rpm, calculated high-speed-shaft torque under 2 kilonewton meter (kN·m), and power less than 150 kW. The single most common operating power was 40 kW. With the higher-rate data, there is far less scatter visible. The power curve is more distinct, and the turbine never generates power at a rotor speed less than 10 rpm, as expected. Another interesting operating condition that is discernable in the 1-second data occurs at approximately 12.7 rpm rotor speed and just over 2 kN·m of torque and up to 260 kW of power. Then, as expected, there is an appreciable period of time when the turbine is operating at the rated rotor speed. The torque and active power can vary widely in this condition, with the torque ranging from 4 kN·m to 11 kN·m and the power ranging from 600 kW to 1,800 kW. The short periods above rated conditions are clearly evident in the 1-second data compared to the 10-minute data.

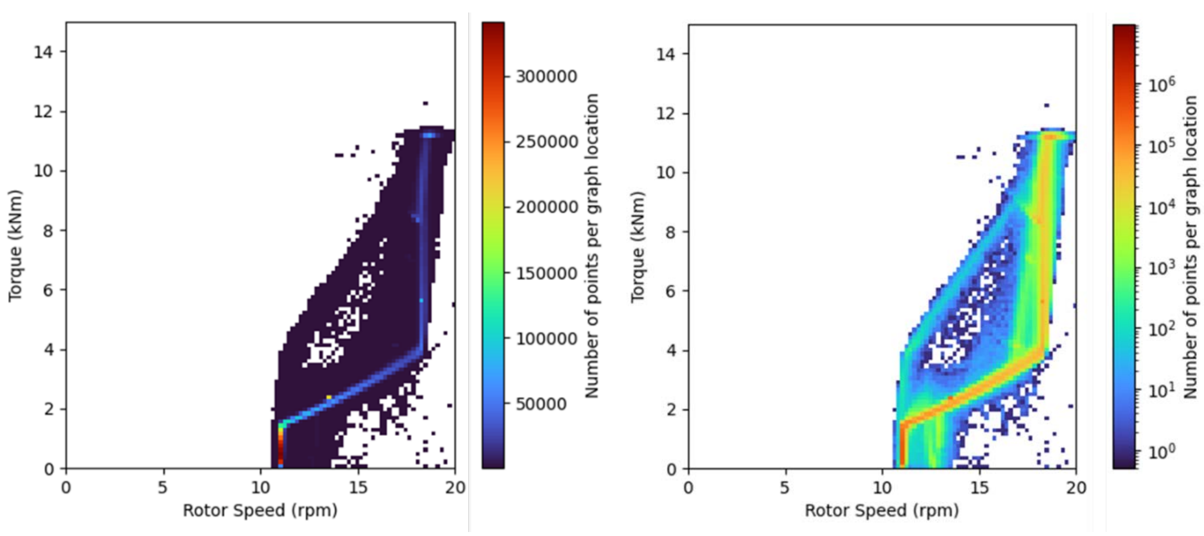

Figure 5. One-second rotor speed and high-speed-shaft torque on linear (left) and logarithmic (right) scales

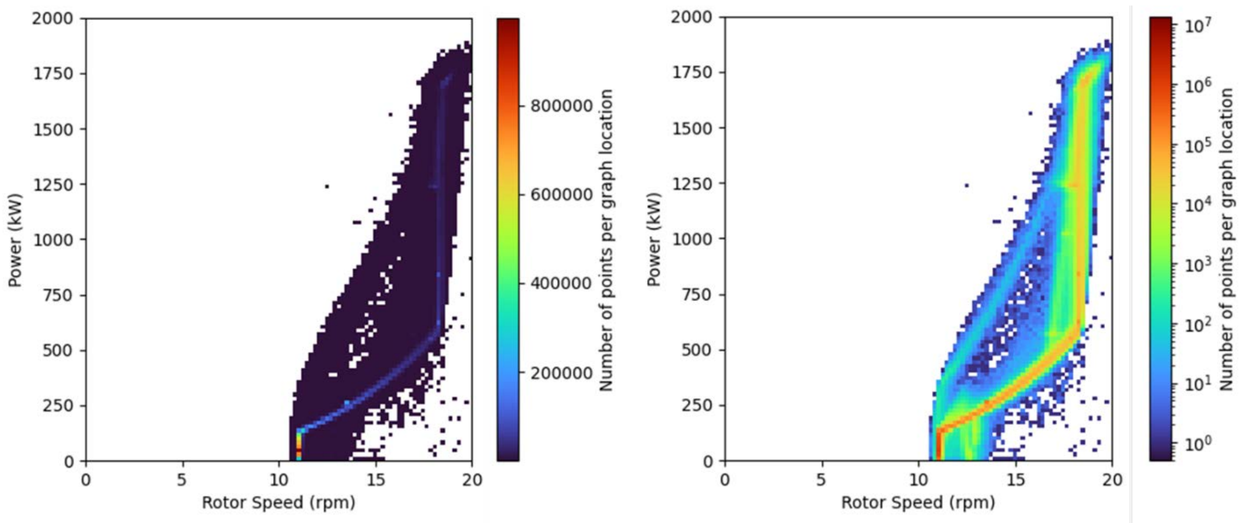

Figure 6. One-second rotor speed and active power on linear (left) and logarithmic (right) scales

3 Summary

Micropitting is an asperity-level fatigue phenomenon that occurs in hertzian contacts in both gears and rolling-element bearings that operate in mixed- or micro-elastohydrodynamic lubrication regimes. It manifests itself in many different ways in gear teeth, and, in some cases, it can be the primary failure mode of a gearbox. Despite much research by many investigators, micropitting remains complex, unpredictable, difficult to control, and a problem in wind turbine gearboxes.

As part of a continuing research effort to investigate gear tooth micropitting, this report documented the usage history of a wind turbine gearbox that experienced micropitting on the sun pinion. The gearbox was installed for slightly more than 8 years and accumulated over 14,000 hours of operational time. The most common operating condition for the turbine was the low-speed, low-power condition at a rotor speed of 11 rpm and torque well under 20% of the rated condition. The second most common condition was at the rated rotor speed of 18.3 rpm with a torque ranging from 40% to rated. Evident only in the high-resolution data is another operating condition at approximately 12.7 rpm rotor speed and 20% torque. The gearbox oil sump temperature was overwhelmingly between 40°C and 60°C. These operational conditions will be used in a forthcoming case study of Method A of ISO/TS 6336-22.

References

Carroll, J., A. McDonald, I. Dinwoodie, D. McMillan, M. Revie, and I. Lazakis. 2017. "Availability, Operation and Maintenance Costs of Offshore Wind Turbines with Different Drive Train Configurations." *Wind Energy* 20(2): 361–378. doi: 10.1002/we.2011.

Castrol. 2009. Product Data Castrol Optigear Synthetic A. https://msdspds.castrol.com/bpglis/FusionPDS.nsf/Files/AD6A642C79F8C79D80257796003012DF/$File/450763_US_en.pdf.

Giammarise, A. and M. Sirak. 2009. "Challenges of Large MMW Gearboxes in Wind Turbine Applications." Sandia Wind Turbine Reliability Workshop: Albuquerque, NM. https://windpower.sandia.gov/2009Reliability/PDFs/Day2-03-AnthonyGiammarise.pdf.

Guo, Y. and J. Keller. 2020. "Validation of Combined Analytical Methods to Predict Slip in Cylindrical Roller Bearings." *Tribology International* 148: 106347. doi: 10.1016/j.triboint.2020.106347.

Keller, J., Y. Guo, and L. Sethuraman. 2019. *Uptower Investigation of Main and High-Speed-Shaft Bearing Reliability*. Golden, CO: National Renewable Energy Laboratory. NREL/TP-5000-71529. http://www.nrel.gov/docs/fy19osti/71529.pdf.

Keller, J., M. Michaud, and S. Lambert. 2020. *Report of the Condition of a General Electric Transportation Systems Gearbox*. Golden, CO: National Renewable Energy Laboratory. NREL/TP-5000-76004. http://www.nrel.gov/docs/fy20osti/76004.pdf.

Lantz, E. 2013. *Operations Expenditures: Historical Trends and Continuing Challenges*. Golden, CO: National Renewable Energy Laboratory. NREL/PR-6A20-58606. http://www.nrel.gov/docs/fy13osti/58606.pdf.

Olson, R., M. Michaud, and J. Keller. 2020a. *Case Study of ISO/TS 6336-22 Micropitting Calculation*. Golden, CO: National Renewable Energy Laboratory. NREL/CP-5000-76776. http://www.nrel.gov/docs/fy20osti/76776.pdf.

Olson, R., M. Michaud, and J. Keller. 2020b. *Case Study of ISO/TS 6336-22 Micropitting Calculation* (Presentation). Golden, CO: National Renewable Energy Laboratory. NREL/PR-5000-77731. http://www.nrel.gov/docs/fy20osti/77731.pdf.

Santos, R., and J. van Dam. 2015. *Mechanical Loads Test Report for the U.S. Department of Energy 1.5-Megawatt Wind Turbine*. Golden, CO: National Renewable Energy Laboratory. NREL/TP-5000-63679. http://www.nrel.gov/docs/fy15osti/63679.pdf.

Sheng, S. 2017. *Wind Turbine Gearbox Reliability Database, Condition Monitoring, and O&M Research Update*. Golden, CO: National Renewable Energy Laboratory. NREL/PR-5000-68347. https://www.nrel.gov/docs/fy17osti/68347.pdf.

Stehly, T., P. Beiter, and P. Duffy. 2020. *2019 Cost of Wind Energy Review*. Golden, CO: National Renewable Energy Laboratory. NREL/TP-5000-78471. https://www.nrel.gov/docs/fy21osti/78471.pdf.

Wiser, R., M. Bolinger, and E. Lantz. 2019. "Assessing Wind Power Operating Costs in the United States: Results from a Survey of Wind Industry Experts." *Renewable Energy Focus* 30: 46–57. doi: 10.1016/j.ref.2019.05.003.

Appendix A. Maintenance Record Summary

Table 1. Gearbox Maintenance Record Summary

Event	Date	Turbine Operation (hr)	Production (kWh)	Viscosity at 40°C (mm^2/s)	Acid Number (mg KOH/g)	Lubricant Particle Count	Water Content (ppm)	Notes
Commissioning	9/28/09	0						
Oil sample	6/710	845		326	2.35	22/18/10	420	
Maintenance	9/22/10	1,328						
Maintenance	12/14/11							
Maintenance	6/29/12	4,539	2,040,148					
Oil sample	7/11/12	~4,500		327	3.14	20/17/12	849	
Oil sample	10/31/12	5,638		326	2.88	23/19/13	435	
Borescope	11/27/12							No damage noted
Maintenance	1/14/13							
Maintenance	3/26/14							
Maintenance	1/29/15	~7,000	3,172,917					Particles in filter
Maintenance	8/8/15							
Borescope	11/6/15							Onset of micropitting
Oil sample	3/11/16	8,584		313	2.74	21/17/12	284	
Maintenance	1/15/17							
Oil sample	6/23/17	12,704		311	2.84	21/18/13	469	
Maintenance and oil sample	9/14/17	13,945		310		21/18/14	890	Black sludge in oil
Oil sample	9/25/17					21/18/14	7,194	
Gearbox removal	12/16/17	14,174	~6,000,000					
Borescope	4/11/18							Micropitting

g = gram, hr = hour, kWh = kilowatt-hour, mg = milligram, mm = millimeter, ppm = parts per million