



Investigation of Various Wind Turbine Drive Train Condition Monitoring Techniques

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ABSTRACT

The wind industry has experienced premature turbine component failures during the past years. With the increase in turbine size, these failures, especially those found in the major drivetrain components, i.e. main shaft, gearbox, and generator, have become extremely costly. Given that the gearbox is the most costly component in the drivetrain to fix, the National Renewable Energy Laboratory (NREL) initiated the Gearbox Reliability Collaborative (GRC) to determine the causes for premature gearbox failures and subsequently, recommend improvements to gearbox design, manufacture, and operational practices. The GRC has two identical test gearboxes, which are planned for a dynamometer and a field test, respectively.

Condition Monitoring (CM) is one research area under the GRC. Its near-term goal is to establish some baseline responses for CM systems based on the dynamometer and field tests. Its long-term goals are to correlate the CM outputs with the turbine operational conditions (e.g., rpm, power, etc.) and/or dynamic measurements (e.g., strain, displacement, etc.) of drivetrain components, identify possible causes for abnormal CM readings and/or component failures, and subsequently, recommend strategies for improvement. The GRC CM will be implemented by integrating stress wave, vibration, and lubricant monitoring techniques. The specific CM systems will be set up in collaboration with their commercial suppliers. These CM techniques will be evaluated in both the dynamometer and field tests. Initial startup tests in the dynamometer have been conducted. This paper discusses some of the preliminary test results.

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INTRODUCTION

The wind industry has experienced premature turbine component failures during the past years. With the increase in turbine size, these failures, especially those found in the major drive train components, i.e. main shaft, gearbox, and generator, have become extremely costly. To reduce the cost of wind energy, the improvement in long-term drive train reliability is critical.

Given that gearbox is the most costly component in the turbine drivetrain to maintain throughout the expected 20-year design life of a wind turbine, the National Renewable Energy Laboratory (NREL) has embarked on the task of revealing the causes and loading conditions that result in the premature failure of wind turbine gearboxes [1] through a consortium called the Gearbox Reliability Collaborative (GRC). The GRC brings together different parties involved in the gearbox design, manufacture, and operation process with the common goal of extending the lifetime of gearboxes. To achieve this goal, the GRC takes a multitrack approach, which includes: extensive measurement of gear and bearing loads and displacements, condition monitoring, dynamometer and field testing, and analysis. The GRC will use two identical test gearboxes for its multitrack approach: one will be tested on NREL's 2.5-MW dynamometer and the other will be field tested in a turbine in a nearby wind plant. By correlating these research tracks, the GRC expects to improve wind turbine gearbox design, manufacture, and operational practice.

Condition Monitoring (CM) is one research area under the GRC. CM systems normally measure data that can supply critical indicators of component operation and performance to identify incipient failures before catastrophic failure occurs [2]. The benefits of CM include [2]: 1) early deterioration detection to avoid catastrophic failure; 2) accurate damage evaluation and subsequently, a cost-effective maintenance or component replacement plan; and 3) root cause analysis and subsequently, an improved operation strategy to reduce chances of structure deterioration. The near-term goal of CM under the GRC is to establish some baseline responses for CM systems based on the dynamometer and field tests. Its long-term goals are to correlate the CM outputs with the turbine operational conditions (e.g., rpm, power, etc.) and/or dynamic measurements (e.g., strain, displacement, etc.) of drivetrain components, identify possible causes for abnormal CM readings and/or component failures, and recommend strategies for improvement. The GRC CM is implemented by simultaneously investigating acoustic emission (AE – specifically stress wave), vibration, and lubricant monitoring techniques. The specific CM systems will be set up in collaboration with their commercial suppliers. These CM techniques will be evaluated in both the dynamometer and field tests. Initial startup tests in the dynamometer have been conducted. This paper discusses some of the preliminary test results.

GRC TURBINE DRIVETRAIN AND GEARBOX INSTRUMENTATION

The GRC turbine drivetrain is composed of the following components: hub, main bearing, main shaft, gearbox, brake, generator shaft, and generator. In terms of CM, the drivetrain typically refers to the main bearing, gearbox, and generator, which are normally monitored by CM systems.

The GRC has two test gearboxes: one is the test article for the NREL 2.5-MW dynamometer and the other is for the field test in a nearby wind farm. With two test gearboxes, it is possible to duplicate the loading conditions obtained from the field in the controlled dynamometer test environment and monitor their dynamic responses. To make the GRC research representative of current technology, the test gearboxes were redesigned to reflect the configuration and characteristics of current industry standards for large-scale wind turbines. To understand their dynamics, the two test gearboxes are heavily equipped with more than 120 channels of instruments. The parameters measured by these instruments include [3]: planet stage bearing roller load distribution, planet stage bearing load sharing, bearing raceway temperature, sun motion with respect to planet carrier, planet carrier misalignment, root stresses on the planet ring mesh, shaft bending, etc. These measurement results can be correlated with the CM system readings to potentially help identify the root causes of certain component failures.

CM APPROACH, RATIONALE AND SYSTEM SETUP

The GRC CM will be implemented through an integrated approach because no single technique can provide the comprehensive and reliable solutions needed by the industry. Each technique has its own strengths and limitations [4]. For example, oil CM (such as particle counts) will not detect machine imbalance, misalignment, shaft cracks, and resonances, which can be complemented by vibration CM. Likewise, vibration CM will not detect water or particles in the lubricant, which requires oil CM. Specifically, the GRC has adopted three CM techniques; 1) AE, 2) vibration, and 3) lubricant. The main reason to combine AE and vibration CM is to extend the measurable dynamic frequency range to above 20 kHz. Vibration can typically be measured in terms of displacement by proximity probes or in terms of acceleration by accelerometers. The proximity probe is not considered here, as it is typically used for shaft displacement measurement. However, the wind turbine main shaft is not a common failure component in the drivetrain and thus not included in this study. Another advantage gained from AE, specifically stress wave monitoring, is the potential to detect abnormal lubricant film thickness [5]. The main consideration in adding oil CM is to combine its early active machine wear detection capability with AE and vibration CM's crack location pinpointing feature [6]. The combination of all three techniques may provide the earliest possible detection of component failure or structural deterioration. GRC's integrated approach is not only in-line with typical industry practices [4], which combines vibration or stress wave monitoring with oil CM, but is also a little above industry standards due to the addition of the third technique. Although the integration of all three techniques may not gain popularity in commercial applications because of the increased cost, it provides the GRC with a unique platform for investigating different CM techniques that are representative of current wind industry field applications.

To set up the CM systems for the three adopted techniques, there are two options: 1) have NREL customize the needed sensors, data acquisition (DAQ) boards, and signal processing algorithms; 2) choose a commercial package under each CM technique and have NREL do a minimal amount of DAQ system customization and signal processing algorithm development. The second option was chosen because it will take less time to implement and will allow the GRC to meet its planned gearbox test schedule.

There are usually several commercial packages available for each CM technique. To decide which package to use for this CM project, the GRC team used the following criteria: 1) use only one CM system for each technique, as presently there is no plan to evaluate different CM packages under the GRC; 2) choose the best possible package (in terms of performance) among interested CM system suppliers; and 3) research previous wind industry experience with the package.

Based on these criteria, through some study and communication with interested CM package suppliers, the systems selected for the GRC CM project include: SKF WindCon for vibration; Swantech SWANwind for AE; and Kittiwake Online Sensor Suite, Macom TechAlert 10, and Hydac CSM 1220 for oil. All but the Hydac package are on loan to NREL for conducting CM research under the GRC.

Although the selection of multiple oil CM packages appears contradictory to criterion 1), each package provides a certain aspect of information on the monitored lubricant and their outputs have no overlaps. Specifically, the Kittiwake Online Sensor Suite is a compact unit capable of measuring three lubricant parameters: total ferrous debris in ppm; relative humidity in percentage; and oil quality (changing with the level of such contaminants as soot, oxidation products, glycol, water, etc.) in customized scale. The Macom TechAlert 10 counts both ferrous and non-ferrous particles and divides each type of particles into five bins. The minimum detectable ferrous particle size is 50 μm and non-ferrous particle size is 150 μm . The Hydac CSM 1220 was purchased by NREL as a laboratory unit to measure the lubricant cleanliness level according to ISO 4406:1999 [7]. This level basically reflects the amount of particles in the following three bins: $>4\ \mu\text{m}$, $>6\ \mu\text{m}$ and $>14\ \mu\text{m}$ for 1 ml of monitored lubricant. Making sure the lubricant is clean to the ISO standard before it is put into a gearbox is very critical for achieving the turbine's expected performance and extending its service life. Comparatively, the selection of SKF WindCon and Swantech SWANwind followed the aforementioned criteria. SKF WindCon was determined to be the best vibration CM system for this project. Swantech SWANwind is one of the few commercial packages using ultrasonic range signals for wind turbine CM.

Figure 1 illustrates the CM system set up for the three packages for the dynamometer test. The SWANguard is the nacelle unit for SWANwind, and the IMx-W is the nacelle unit for WindCon. The Swantech system collects data from not only the main components of the turbine drivetrain, but also the motor and gear of the dynamometer. It is composed of two SWANguard units: one is set up for collecting data from the main drivetrain components in synchronized mode, and the other is set up for collecting data from the entire drivetrain and dynamometer gear and motor in sequential mode. The lubricant CM systems only have sensors on the gearbox, as the main bearing and generator do not have a lubrication system. The SKF system monitors the condition of the main components of the turbine drivetrain. All but the CSM 1220 data can be remotely accessed using a web browser. Such a capability enables remote drivetrain CM, CM package troubleshooting, and data analysis.

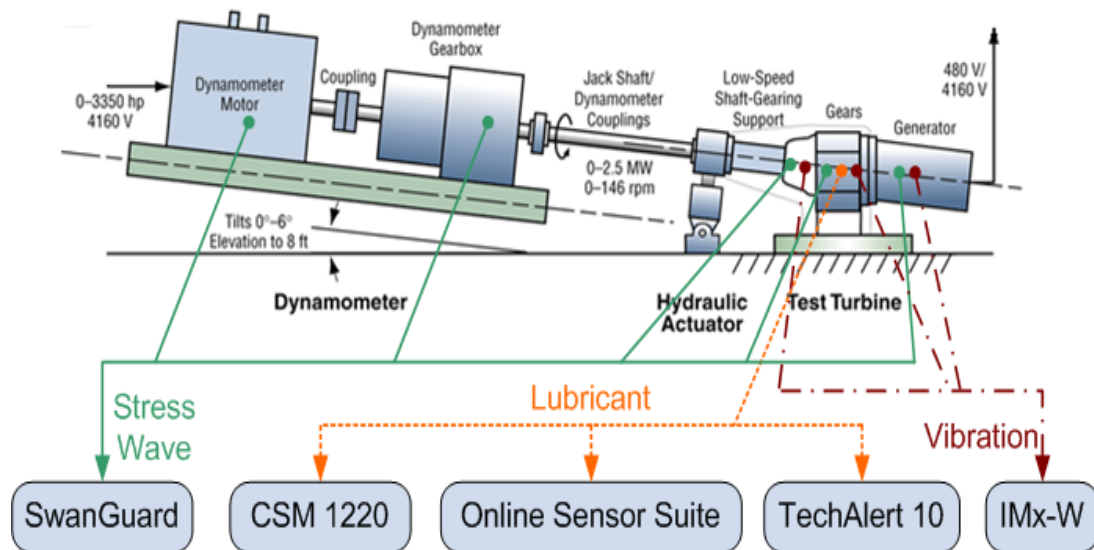


Figure 1. CM system set up for the dynamometer test.

Two changes will be made to the CM system set up on the dynamometer for the field test, 1) removal of CSM 1220, as its main purpose is to ensure the field turbine gearbox starts with clean oil; and 2) reconfigured sensor locations and data acquisition mode for the SwanTech system, as no dynamometer gear or motor will be available in the field turbine. A decision on whether to use the synchronized or sequential data acquisition mode will be made based on the dynamometer test results.

PRELIMINARY TEST RESULTS

The GRC project is a work in progress. Initial dynamometer tests have been conducted. This section will report some preliminary results obtained during a test conducted between 14:46 and 15:09 PM (US MST) on May 4th 2009.

The first set of results (Figure 2) was obtained by the SKF vibration-based CM technique. The high speed shaft (HSS) accelerometer was mounted radially to the HSS on the back cover of the test gearbox. The planet stage accelerometer was mounted on the bottom of the ring gear at around a 6:00 o'clock position. The data was collected at around 15:01, see Figure 3 (left), when the generator was connected to the grid (on line) and running at around 1201 rpm. Figure 2 (left), the spectrum of acceleration collected from the HSS, shows that the intermediate speed shaft (ISS) and HSS gear mesh frequency is 440 Hz and its harmonics are also identifiable. Figure 2 (right), the envelope analysis of acceleration collected from the planet stage, shows that the component vibration frequencies with amplitude greater than > 0.00035 g, from left to right, include: 0.25 Hz, main shaft rotational frequency; 0.75 Hz, rotor rotational frequency; 2.81 Hz, 2nd harmonic of LSS rotational frequency; 15 Hz, 2nd harmonic of planet carrier (PLC) downwind bearing ball passing frequency inner raceway (BPFI); 20 Hz, generator or HSS rotational frequency; 25 Hz, 2nd harmonic of LSS downwind bearing ball spinning frequency (BSF); and 30 Hz, LSS downwind bearing BPFI. From these results, it is reasonable to infer that accelerometers are normally capable of catching changes in gear meshing, shaft rotation, and

bearing characteristic frequencies. By trending the amplitudes of these frequencies over the operational time of a wind turbine, the changes in the condition of the monitored components can be detected. The BPFIs observed in Figure 2 (right) may imply deterioration in planet carrier and LSS downwind bearings, but this will require disassembly for verification.

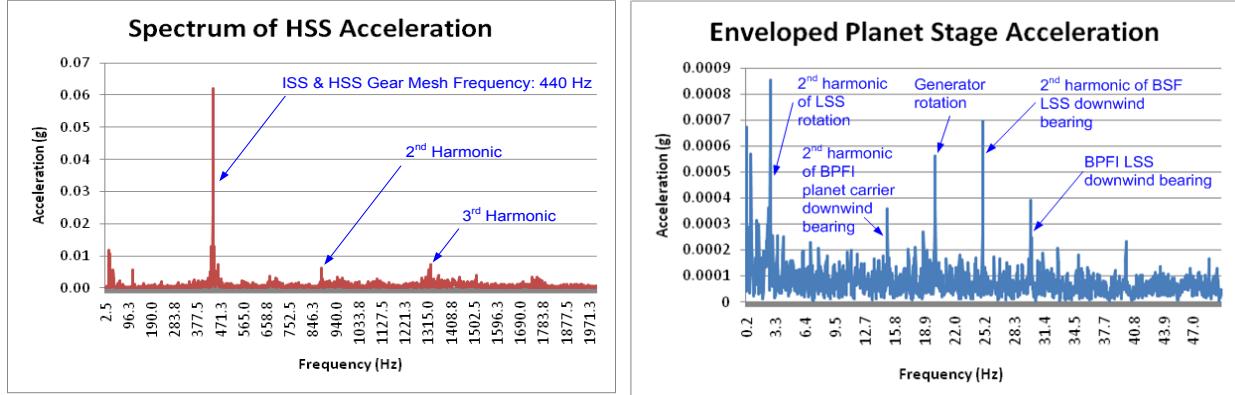


Figure 2. Readings from vibration-based CM technique.

The second set of results (Figure 3) was obtained by the SwanTech AE-based (or stress wave) CM technique. The main bearing sensor was mounted in a radial direction. The ring gear sensor was mounted on the top of the ring gear at around the 12:00 o'clock position. The helical gear sensor was mounted axially in the middle of all three shaft ends on the back of the test gearbox. The generator sensor was mounted on the drive end in a radial direction. The data was collected throughout the test from 14:46 to 15:09. Figure 3 (left), the generator speed and dynamometer motor power, shows that the generator was ramping up at around 14:46 and connected to the grid at around 14:49. The generator stayed online until around 15:08. In Figure 3 (right), which shows the stress wave energy (SWE) obtained by the four sensors as mentioned above, it appears there are two pairs of strong correlations: the generator RPM with the SWEs obtained at the main bearing and generator; and the dynamometer motor power with the SWEs obtained at the ring gear and helical gear. The calculated correlation coefficients, 0.97 for the main bearing and 0.92 for the generator, and 0.95 for the helical gear and 0.89 for the ring gear, verified this observation. The second pair of correlations implies that the SWEs obtained at the ring and helical gears might be an indicator of the driving load to the gearbox, which is normally not measured in a field turbine. The weak correlations between the generator RPM and the SWEs obtained at the ring and helical gears (0.56 for the ring and 0.54 for the helical gear) reflects the complex dynamics and strong signal attenuation from the rotational shafts to these two sensor locations. On the other hand, the elevated SWEs obtained at around 15:03 by the ring and helical gear sensors may be additional evidence of deterioration in planet carrier and LSS downwind bearings.

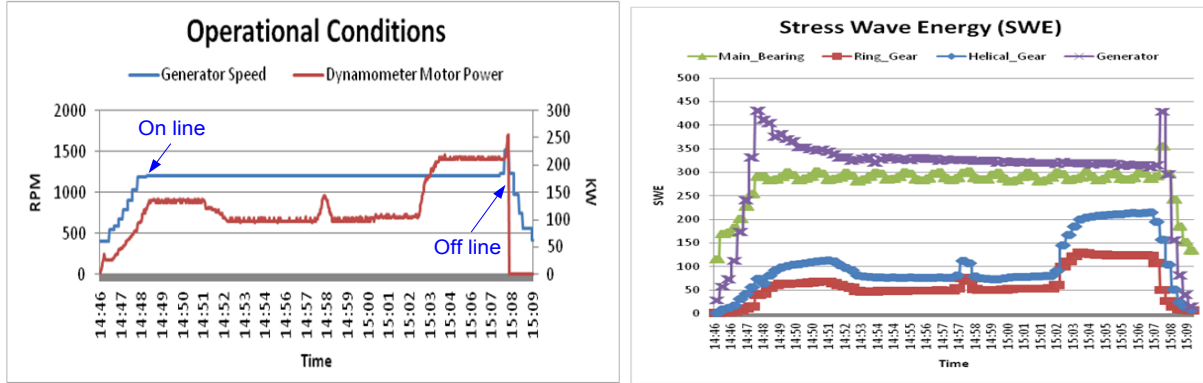


Figure 3. Readings from AE-based CM technique.

The third set of results (Figure 4) was obtained from the oil CM technique. The generator status is labeled in Figure 4 and divided into three stages: around 13:51, the generator speed started ramping up; around 13:59, the generator was connected to grid; and around 14:10, the generator went off grid but the lubricant CM system was left running. At around 14:34, the power supply to all CM systems shut off and all oil cleanliness level readings dropped to 0s, which are not shown in the figure. Figure 4, the oil cleanliness level according to ISO 4406:1999, shows that throughout the gearbox operational process (before the generator went off line), a broad range of particle sizes were generated, as demonstrated by the increased oil cleanliness level in all three bins ($> 4 \mu\text{m}$, $> 6 \mu\text{m}$, and $> 14 \mu\text{m}$). This verified that wind turbine gearboxes always emit particles. It is worth noting that the larger the number, the more contaminated the oil. It is also observed that the oil cleanliness level decreases with the ramping up of the generator speed and increases with the shutdown of the generator and continuously functional lubricant filtration system. Therefore, the oil cleanliness level can potentially be used for run-in of wind turbine gearboxes. It is expected that the oil cleanliness level will increase when the run-in at a certain load level starts and it will gradually stabilize due to the smoothed contacting surfaces obtained through run-in and the continuously functional lubricant filtration system, which can be used to determine when run-in of wind turbine gearbox is done for a certain load level. Comparatively, the results obtained from the other two oil CM systems have not shown such subtle changes in particle counting, debris level, moisture, or oil condition, with the ramping up and down of the generator operational speed. However, these oil CM systems are not intended for measuring the lubricant ISO cleanliness levels. Rather they are designed for long-term operation and might not be applicable for run-in of wind turbine gearboxes.

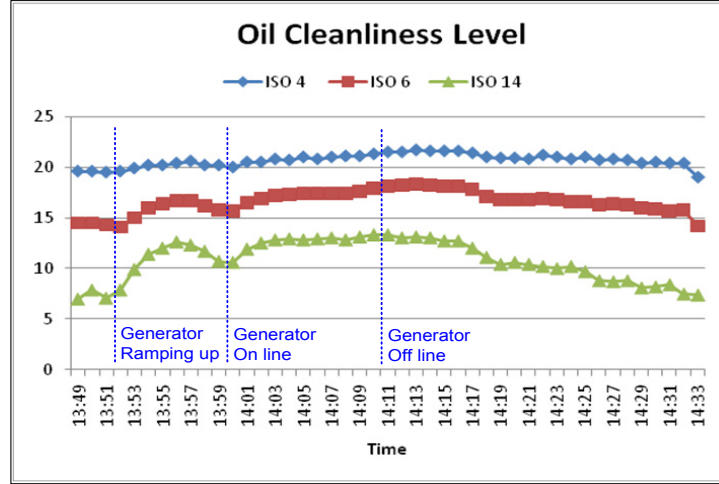


Figure 4. Readings from oil CM technique.

CONCLUSIONS & FUTURE WORK

This paper presented an overview of the CM work under the GRC project and some preliminary dynamometer test results. From the reported test results, it is clear that different CM techniques reveal different details of the monitored drivetrain components. Vibration is capable of pinpointing crack location on bearings or gears. By trending the amplitude of certain characteristic frequencies of the monitored component over time, the deterioration or condition of the monitored component could be detectable. Although no results of spectrum analysis on the SWE time series were reported in this paper, it also has the potential for crack location pinpointing. This will be evaluated and reported in future publications. The SWEs obtained at the turbine gearbox might be useful for inferring its driving load.

The amount of particles as measured by the ISO oil cleanliness level increases and decreases as the turbine speed ramps up and down. These results indicate that the measurement of oil cleanliness level might be useful for run-in of wind turbine gearboxes. Comparatively, the oil CM systems, not measuring down to the ISO cleanliness level, might be designed for long-term turbine operation and not applicable for run-in of wind turbine gearboxes. The increase in a broad range of particle sizes also verified that wind turbine gearboxes always emit particles.

The GRC will continue the dynamometer test of the first gearbox, which will be moved to the field once its run-in is done. The second gearbox, currently being assembled, will then be installed on the dynamometer. After the run-in of the second gearbox is completed, loading conditions obtained from the field test gearbox will be mimicked in the dynamometer. As the investigation of all three CM techniques continues, data will be collected from both the dynamometer and field tests. Correlations between the CM readings and the drivetrain component loading and operational conditions will be studied. Improved operational or control strategies will be proposed when appropriate. Data fusion techniques will be investigated, in collaboration with the CM system supplier and other research institutes, to achieve the automatic delivery of useful information to wind turbine field operators.

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