Wind Turbine Drivetrain Condition Monitoring – An Overview

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WIND TURBINE DRIVETRAIN CONDITION MONITORING – AN OVERVIEW

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Abstract: Wind energy is presently the fastest growing renewable energy source in the world. However, the industry still experiences premature turbine component failures, which lead to increased operation and maintenance (O&M) costs and subsequently, increased cost of energy (COE). To make wind power more competitive, it is necessary to reduce turbine downtime and increase reliability. Condition monitoring may help by reducing the chances of catastrophic failures, enabling cost-effective operation and maintenance practices, and providing inputs to improve turbine operation, control strategy, and component design. As compared with other applications, the wind industry started recognizing the benefits and importance of condition monitoring relatively late. However, interest has increased so much that a workshop was organized by the National Renewable Energy Laboratory (NREL) in 2009 as a response. This paper provides an overview of wind turbine drivetrain condition monitoring based on workshop presentations and additional references. Since the gearbox has been shown to have the longest downtime and is the most costly subsystem to maintain throughout a turbine's 20 years of design life, it has been chosen as the main targeted subsystem of this study. Wind turbine drivetrain condition monitoring practices, challenges, and future research opportunities will be addressed in detail.

Key words: Condition monitoring; gearbox; oil sample analysis; real-time oil monitoring; vibration analysis; wind turbine

Introduction: Wind energy is presently the fastest growing renewable energy source in the world. By the end of 2009, the global cumulative installed wind capacity had reached more than 159 GW with about 10 gigawatts (GW) of wind energy installed in the United States in 2009 alone [1]. However, the industry still experiences premature turbine component failures, which leads to increases in operation and maintenance (O&M) costs and subsequently, the cost of energy (COE). Considering accelerated offshore wind installation and the increase in turbine size, these failures will be extremely costly. As a result, there is a need for the industry to reduce turbine downtime and increase reliability. Condition monitoring (CM), defined as the process of monitoring a parameter of

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condition in machinery such that a significant change is indicative for a developing failure [2], can potentially help by: 1) detecting incipient failures early, thereby reducing the chances of catastrophic failures; 2) accurately evaluating component health conditions, which has the potential to enable more cost-effective O&M; and 3) analyzing root causes, which may provide the inputs for improved turbine operation, control strategy, and component design.

Although CM did not receive much attention in the wind industry until about two decades ago, interest has increased dramatically during the past several years due to the growth of the global wind industry and the huge potential of CM in reducing COE for wind power, especially when turbines are deployed offshore. In response to such increased interest, a workshop on wind turbine condition monitoring was organized by the National Renewable Energy Laboratory (NREL) in 2009. The workshop covered a broad range of topics [3], including economic benefits, current CM practices, drivetrain monitoring, lubricant conditioning and monitoring, structural health monitoring, research and development efforts, and CM practices in other industries. This paper is not intended to provide a recap of the workshop or a thorough review of wind turbine condition monitoring techniques, but rather it provides an overview of wind turbine drivetrain condition monitoring based on workshop presentations [4] and additional references.

In a broad sense, CM of an onshore utility-scale wind turbine can target almost all of its major subsystems, including blades, nacelle, drivetrain, tower, and foundation. There are several guidelines on the requirements of CM systems for wind turbines available in Europe [5, 6] that can be used as the starting points for conducting CM research or CM product development. The CM discussed in this paper is more narrow, however, and focuses on the monitoring of wind turbine drivetrains. Figure 1 illustrates the main components of a typical utility-scale wind turbine drivetrain, which includes the main bearing, main shaft, gearbox, brake, generator shaft, and generator. From the perspective of CM, the three major monitored drivetrain components are the main bearing, gearbox, and generator. Of these three components, and as shown in Figure 2, (derived from the 2003 to 2009 data published by Wind Stats Newsletter [7]), the gearbox caused the longest downtime. Other sources have also revealed that the gearbox is the most costly subsystem to maintain throughout a turbine’s 20 years of design life [8]. For this reason, the gearbox has been chosen as the main targeted subsystem of this study. In detail, this paper will cover the typical practices, challenges, and future research opportunities related to wind turbine drivetrain CM.

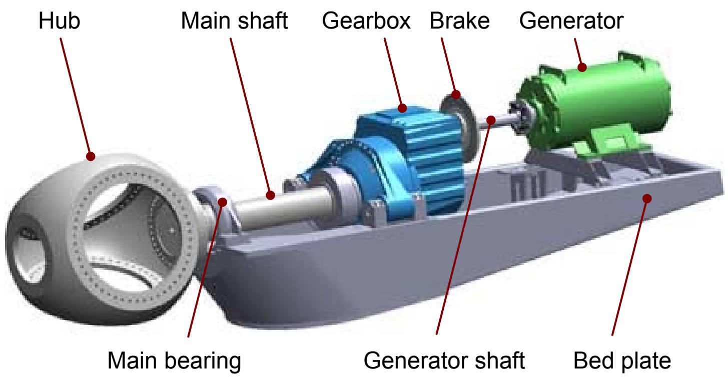


Figure 1: Typical Utility-scale Wind Turbine Drivetrain

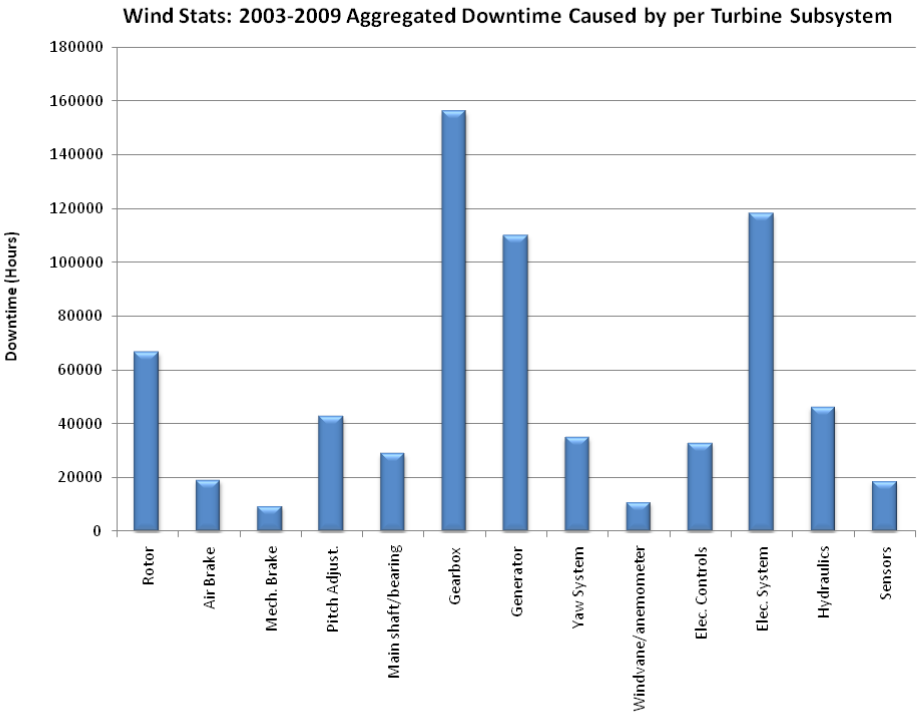


Figure 2: Aggregated Downtime Caused by Turbine Subsystems [7]

Wind turbine gearbox: Utility-scale wind turbines are designed to operate in remote locations, where strong winds are available. The turbine nacelle is sitting on top of a tower which is normally more than 60 meters (m) in height. The blades can be adjusted through the yawing system to face wind direction and blade pitch angles can also be tuned to control speed through the pitching systems. Inside the nacelle of a geared turbine, the gearbox is placed between the hub and the generator and used to convert the slowly rotating high torque power from the wind turbine rotor to high speed low torque power used by the generator. Figure 1 represents the three-point suspension concept for the mounting of the gearbox in a wind turbine. One point is the main bearing and the other two points are the gearbox torque arm supports. In such a configuration, some of the loads transmitted from the rotor to the generator will go through the gearbox [9].

The internal configuration of a wind turbine gearbox varies according to the manufacturer or model. One configuration widely adopted by the industry is illustrated in Figures 3 and 4. It has one low-speed planetary stage and two parallel stages. The planetary stage is composed of one planet carrier (PLC), one annulus gear, and three planets. The planets are coupled with the annulus and the sun gear, which is further connected to the gear on the low-speed shaft. Bearings of several different types are often employed in wind turbine gearboxes according to the loading conditions and gearbox life requirements. In the gearbox shown in Figures 3 and 4, the PLC is supported by two full-complement cylindrical roller bearings (fcCRB) and each planet gear is supported by two identical cylindrical roller bearings (CRB). Each parallel shaft (i.e., low, intermediate, and high speed) in the gearbox is supported by a CRB on the upwind (rotor) side of the assembly, and by two back-to-back mounted, tapered roller bearings (TRB) on the downwind (generator) side. Lubrication oil is another important component in a wind turbine gearbox. The main functions of lubricant are [10]: 1) lubrication: reduces friction and wear by introducing a lubricating film between moving parts; 2) cooling: helps dissipate heat away from the critical parts of the equipment; 3) cleaning and suspending: facilitates smooth operation of equipment by removing and suspending products, such as carbon, sludge and varnish; and 4) protection: prevents metal damage due to oxidation and corrosion.

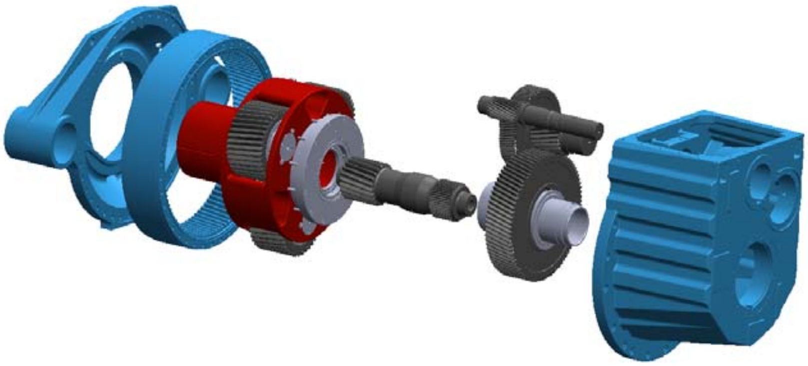


Figure 3: A Typical Wind Turbine Gearbox Configuration

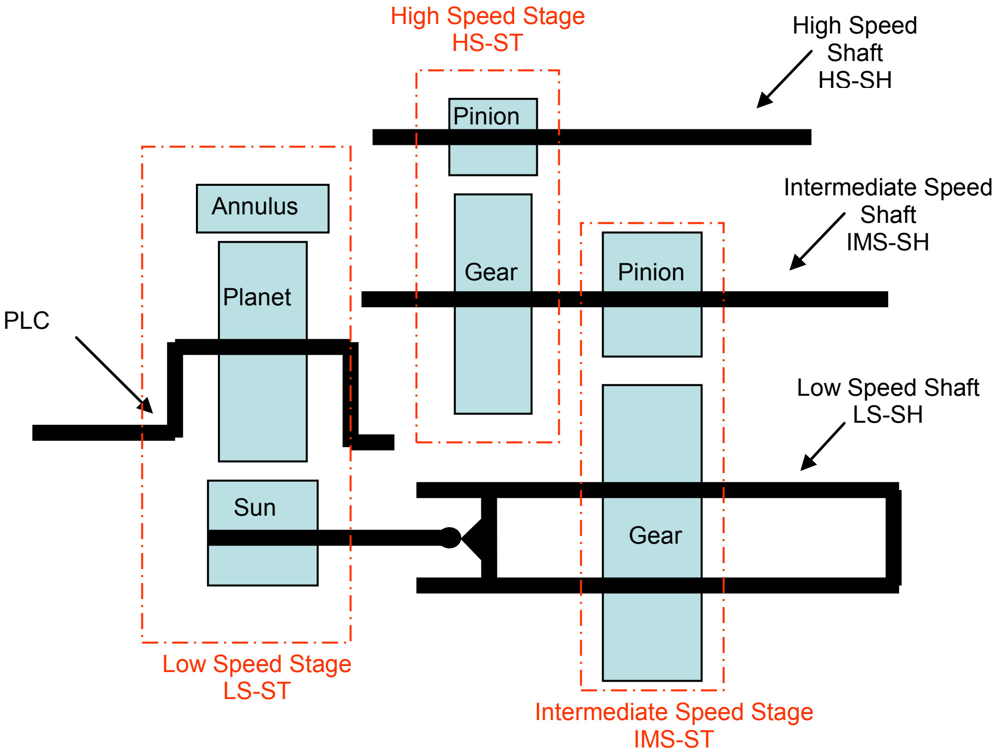


Figure 4: Gearbox Internal Nomenclature and Abbreviations

CM of wind turbine gearbox: From the CM perspective, a wind turbine gearbox consists of three major components: gears, bearings, and lubricant. Some failures observed on these three components are illustrated in Figure 5. The task for CM is to detect these failures at an early stage without disassembly of the gearbox so that condition-based maintenance can be achieved. Although the economics of deploying CM for a wind park is case dependent [11], some studies have shown the estimated return on assumed cost being better than 10:1 [12], with total return on investment achieved in less than three years [13]. These benefits will be even more dramatic if turbines are installed offshore where accessibility is a huge challenge.

(a) Bearing cracks: inner raceway (left [14]) and rollers (right [12])

(b) Gear tooth fracture [15] (c) Lubricant contamination [16]

Figure 5: Examples of Wind Turbine Gearbox Failures (Photo credit: NREL)

Once the economic benefits of CM have been justified, a wind park owner/operator needs to establish an appropriate monitoring strategy, which will be more meaningful with defined observable symptoms related to wind turbine gearbox failures. Examples of such symptoms include:

- Elevated vibrations
- Increased noise level
- Oil contamination
- Overheating
- Component performance degradation

In addition, the following monitoring techniques can be considered [17]:

- Vibration analysis
- Acoustic measurements
- Oil monitoring
- Thermography
- Process parameter or component performance monitoring
- Visual inspection

Among these different techniques, vibration analysis and oil monitoring are the most predominantly used for wind turbine applications. The possible reason for this might be their established successes in other industries. Both techniques can be applied online, otherwise known as continuous data acquisition, and offline, or periodic data acquisition. In addition, a wind farm owner/operator will typically combine these two techniques in order to cover a broader range of potential failures and to increase the credibility of the CM results. For example, vibration analysis can pinpoint the crack locations but oil monitoring cannot. On the other hand, vibration analysis cannot detect lubricant deterioration but oil monitoring can. Therefore, due to their widespread use, the following discussion will be on vibration analysis and oil monitoring techniques.

Vibration analysis: In wind turbine CM, vibration analysis has typically been used to monitor all three key components of a wind turbine drivetrain: the gearbox, main bearing, and generator. Given the complex dynamics experienced by wind turbines, online continuous vibration monitoring is normally recommended. Figure 6 provides a sample setup for a vibration-based wind turbine CM system. It consists of several sensors (accelerometer, acc., signals) and a data acquisition system (DAS), referred to as the condition diagnostics system (CDS enclosure), which are located in the turbine nacelle, and a data server (CDS server) located at the wind park or a remote monitoring center. Typically, the DAS has a channel for the shaft rotational speed signal, which is either measured by a tachometer dedicated to the CM system or supplied by the turbine controller. The communication between the DAS and the data server located at the wind park can be through Ethernet or fiber optic cables. If no data server is set up at the local wind park, the DAS normally can be configured to wirelessly transmit the test data to a server located in the remote monitoring center, which could be anywhere around the globe. The data server normally hosts the CM software package, which is a platform for reviewing and analyzing the data, presenting the CM results, and streamlining both raw and processed data into a CM database. One wind park, typically consisting of hundreds of turbines, can be monitored by one CM software package, if there is no problem in communication between the CM DAS units and the data server.

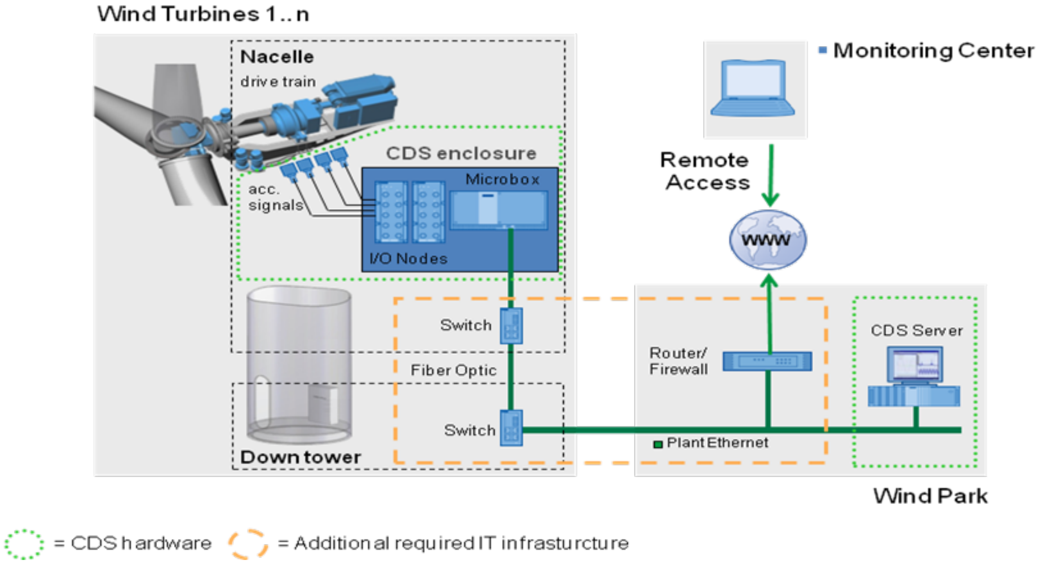


Figure 6: A Sample Setup for a Vibration-based Wind Turbine CM System [18]

Among vibration-based CM systems, the main differences are the number of sensors, measurement locations, and analysis algorithms, since almost all systems use standard accelerometers as the main physical measurement device. Figure 7 demonstrates a comprehensive sensor deployment strategy, which basically covers almost all possible accelerometer mounting locations for vibration-based CM systems seen in the wind industry today. The sensor notations are given in Table 1 and their physical installations are illustrated in Figure 8. This setup was used in the NREL gearbox reliability collaborative CM research. It is worth noting that a typical commercial CM system will have only a portion of these 12 sensors as listed in Table 1. One typical configuration consists of eight accelerometers: two on the main bearing, including one in the radial direction (AN1), and the other in the axial direction (AN2); four on the gearbox, including one for planetary in the radial direction (AN3 or AN4) and one for each stage of the gearbox, i.e. LS-SH (AN5), IMS-SH (AN6), and HS-SH (AN7), all in the radial direction; and two on the generator, including one on the drive end (AN11) and the other on the non-drive end (AN12), both in the radial direction. The other typical configuration also consists of eight accelerometers and the difference from the first is to replace AN5 to 7 with AN8 to 10.

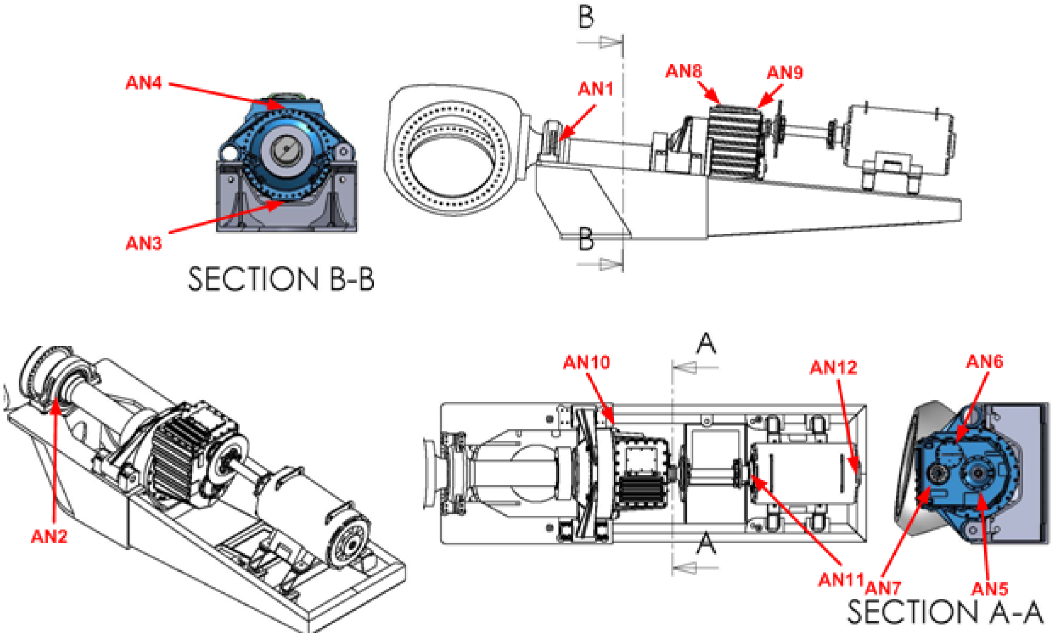


Figure 7: A Comprehensive Sensor Deployment Strategy for Vibration-based CM

Table 1: Sensor Notations and Descriptions

Sensor Label	Description
AN1	Main bearing radial
AN2	Main bearing axial
AN3	Ring gear radial 6 o'clock
AN4	Ring gear radial 12 o'clock
AN5	LSS radial
AN6	ISS radial
AN7	HSS radial
AN8	HSS upwind bearing radial
AN9	HSS downwind bearing radial
AN10	Carrier downwind radial
AN11	Generator drive end radial
AN12	Generator non-drive end axial

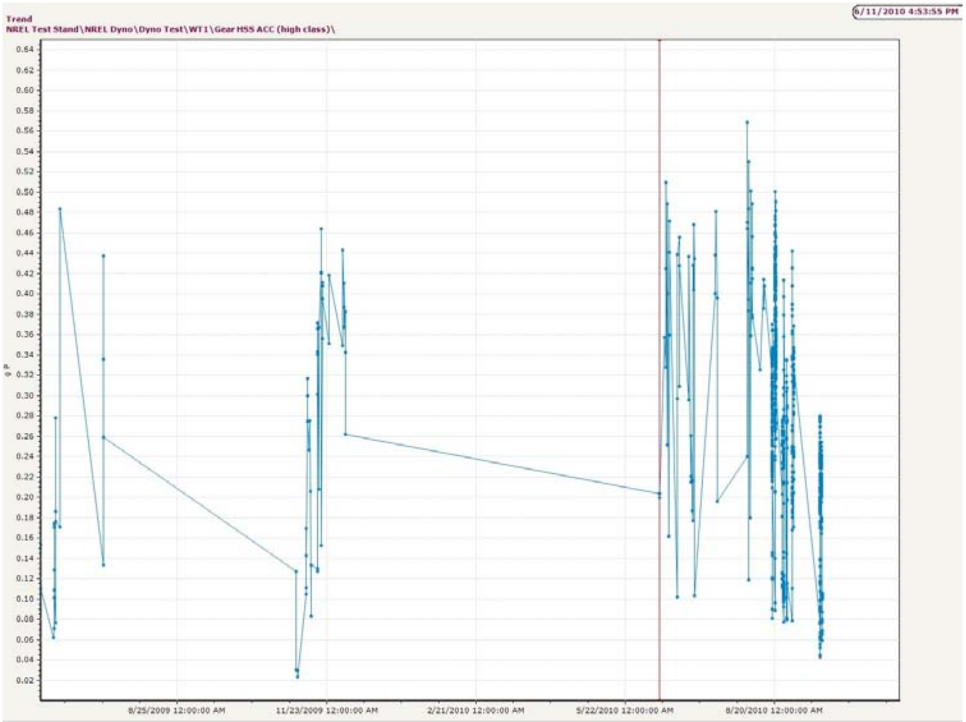
(a) AN1, AN2, AN3, and AN4 (From left to right)

(b) AN5, AN6, AN7, and AN8 (From left to right)

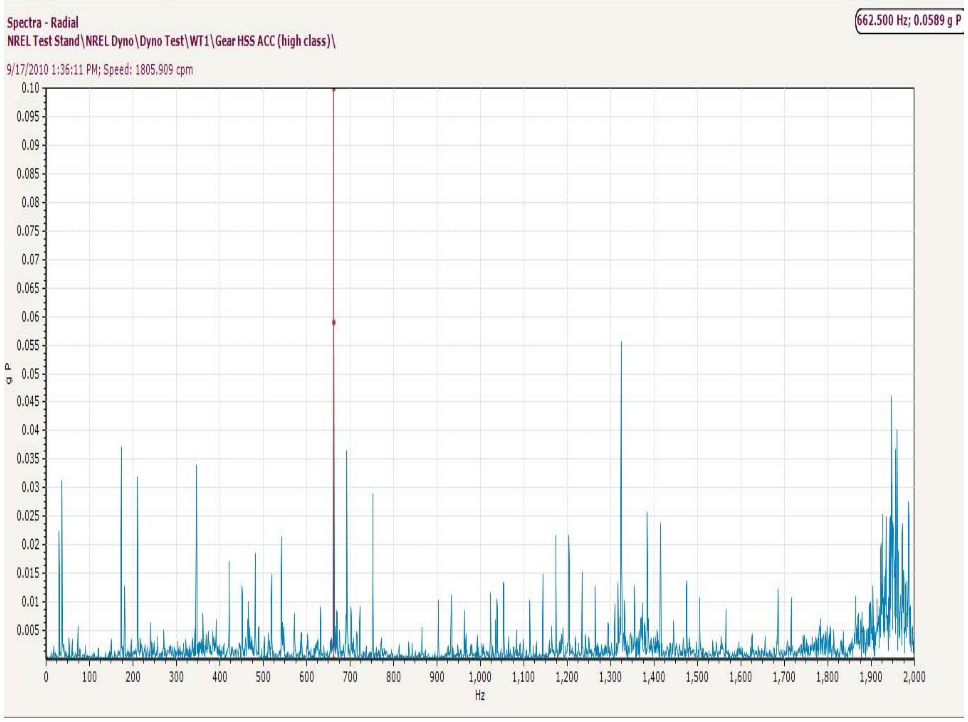
(c) AN9, AN10, AN11, and AN12 (From left to right)

Figure 8: Physical Installation of Accelerometers for Wind Turbine Drivetrain CM
(Photo credit: NREL)

In terms of analysis algorithms, different CM systems may have different approaches. However, almost all of the commonly used algorithms can be classified into two categories: time and frequency domains. For time domain, the monitored parameters may include [19,20] peak, root mean square (RMS), crest factor (i.e., the ratio between the amplitude and RMS within a defined time window), peak-to-peak interval, mean, standard deviation, skewness, and kurtosis. For frequency domain, the common practices are standard fast Fourier transform (or spectrum), order analysis, envelope analysis (or amplitude demodulation), and side band analysis [19]. Frequently, the time domain parameters are used to monitor the trend of overall vibration level over time at a specific measurement location. One triggering mechanism, such as time interval-based or vibration level-based, can be set up in the time domain parameter overall trending process. Whenever it triggers, a discrete frequency analysis snapshot can be taken. Based on these snapshots, detailed examinations on the gearbox health can be conducted. Also, the amplitude of characteristic frequencies for gears (e.g., meshing frequency) and bearings (e.g., ball passing frequency) can be trended over time for detecting potential failures [13]. Figure 9 shows some results obtained from the NREL CM research. The top is an example plot of overall trending of vibration peak value (unit: g) versus the date measured at one sensor location and the bottom is a snapshot of detailed frequency analysis (horizontal axis: Hz and vertical axis: g).



(a) Overall trending of vibration peak value



(b) Frequency analysis snapshot

Figure 9: Sample Results from a Vibration-based CM System

Along the line of vibration analysis, another popular CM technique used by the wind industry is called stress wave analysis [21]. It uses specially designed stress wave sensors to pick up the stress waves (acoustic emissions) generated by the frictional and strike events in a monitored structure. These sensors, along with a tachometer, are connected to an up-tower unit, which communicates with a data server located at either the tower base or in the control room at a wind park. A typical system setup for wind turbine drivetrain monitoring has five stress wave sensors: one on the main bearing in the radial direction; two on the gearbox, including one on the ring gear in the radial direction and the other on the back (downwind or generator side) of the gearbox to measure the parallel stages, mounted in the axial direction; and two on the generator, including one on the drive end and the other on the non-drive end both in the radial direction. Most of the vibration analysis algorithms mentioned earlier are also applicable to stress wave analysis. One unique result provided by the stress wave technique is called a stress wave amplitude histogram, which is illustrated in Figure 10. The left plot indicates that the helical gear is healthy and the right plot indicates that the helical gear is abnormal [22].

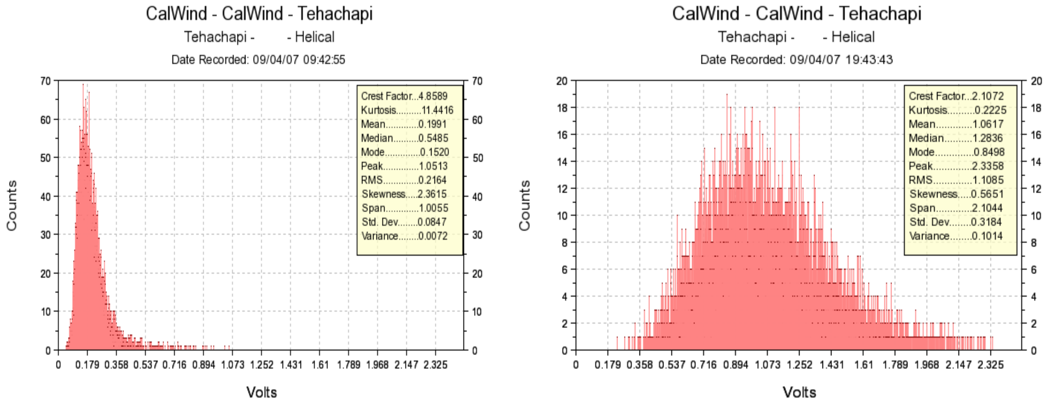


Figure 10: Stress Wave Amplitude Histogram: Healthy (Left) and Abnormal (Right) [22]

Oil monitoring: For wind turbine drivetrain CM, oil monitoring is typically applied to the gearbox, as it is the only oil-lubricated component in the drivetrain. The objective of oil monitoring [23] is to detect oil contamination and degradation. The contamination can be caused by dirt, wear debris, water, incorrect oil, and so on. The degradation can result from depletion of additives, oxidation, base stock breakdown, and so on. Oil monitoring can help detect lubricant, gear, and bearing failures and is an important factor in achieving maximum service life for wind turbine gearboxes [10]. Typical oil monitoring techniques can be divided into two categories: real-time continuous monitoring and offline oil sample analysis. Real-time continuous monitoring can have one or up to several sensors installed in the gearbox lubrication loop. These sensors can be divided into two groups: particle counting sensors, which measure total particle counts, as well as ferrous and nonferrous particles in different size bins, and oil condition sensors, which measure changes in oil quality caused by acidic level, water content, and so on. When the gears and bearings start to fail, the particle generation rates observed during normal turbine operation will increase dramatically and could be detected by the particle counting sensors. With the increase of service time, especially under harsh environmental conditions where wind turbines are usually located, oil quality may deteriorate, which is expected to be detectable by the oil condition sensors. The outputs of these sensors can be viewed in several different ways: 1) within the software package for a vibration-based CM system, which requires the outputs of the oil sensors to be transmitted to the up tower unit of the CM system by following a certain communication protocol; 2) on a computer located at either the tower base or in the control room on a wind park (the computer hosts software packages supplied by the sensor suppliers for managing these sensor outputs); and 3) a website on the internet, the oil sensors need to be configured so that data can be wirelessly transmitted to a remote server, where a web portal has been set up to manage the sensor outputs. Offline oil sample analysis first involves taking an oil sample from the gearbox lubrication system and then sending the sample to a dedicated laboratory for analysis. An analyst at the oil analysis laboratory will review the results and provide recommendations to the owner/operator of the test turbine. The main reasons to include offline oil sample analysis in addition to the real-time continuous monitoring are [23] to:

- Monitor parameters not covered by real-time instruments
- Conduct elemental analysis so that failed components can be indentified
- Assist root cause analysis for some component failures.

The typical parameters sought in an oil sample analysis include [24] particle counts, water content, total acid number, viscosity, and particle element identification. The recommended interval for oil analysis, as stated by wind turbine manufacturers, is typically one sample every six months. However, if the real-time instruments reveal abnormal conditions, it is better to conduct spot oil sample analyses which may help in identifying component failures in progress.

Figure 11 is a lubrication system diagram for the gearbox tested at the NREL 2.5 MW dynamometer test facility. It includes almost all typical practices for real-time continuous oil monitoring seen today in the wind industry. The real-time monitoring sensors are installed both in the inline filter loop, shown as K1, and the offline filter loops, shown as, K2, K3, ISO cleanliness level, and oil quality and moisture sensors. K1, K2, and K3 are particle counting sensors and K1 provides accumulated particle counts. K2 and K3 provide both total accumulated particle counts and ferrous/nonferrous particles in different size bins. ISO cleanliness level is also a measure of contamination of monitored oil, but down to a much smaller particle size as compared to those measured by K1, K2, and K3. Oil quality and moisture sensors are used to monitor oil degradation. For most wind turbine field operations, only one of these real-time sensors is installed.

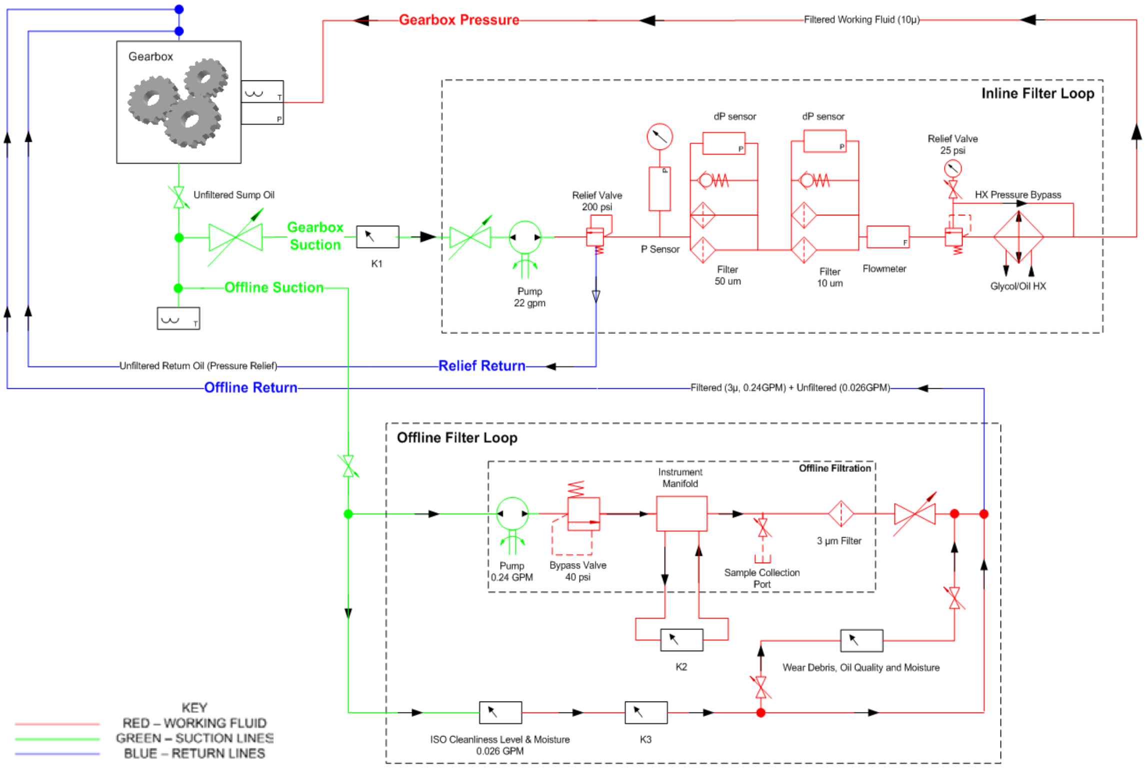
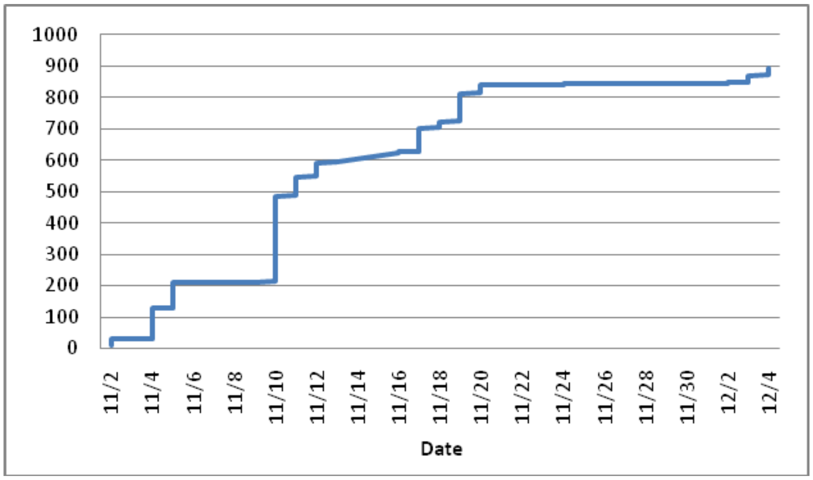


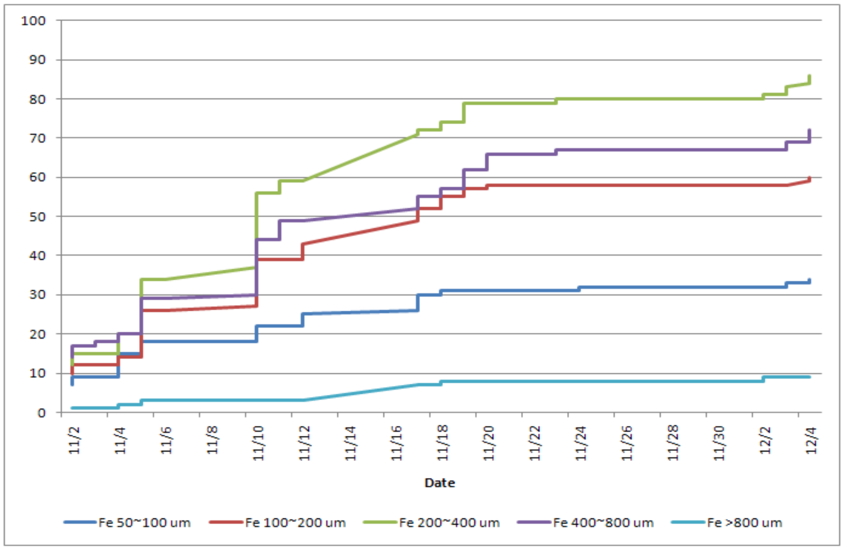
Figure 11: Illustration of Typical Real-time Continuous Oil Monitoring [23]

Figure 12 illustrates some results obtained from the NREL CM research. The test was conducted from November 2 to December 4, 2009, as illustrated in the horizontal axes of plots (a) and (b). Plot (a) is the total accumulated particle counts obtained by sensor K1.

Plot (b) is the ferrous particle counts in five size bins obtained by sensor K2. These results indicated that the test gearbox appeared healthy at the end of the test.



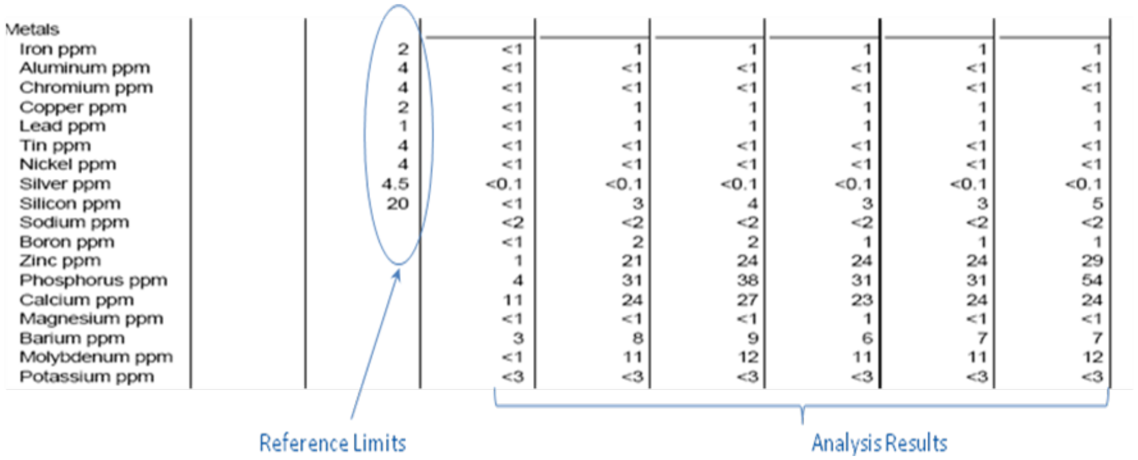
(a) Particle Counts Obtained by Sensor K1



(b) Ferrous Particle Counts Obtained by Sensor K2

Figure 12: Sample Results Obtained by Real-time Oil Monitoring Sensors

In the NREL CM research, offline oil sample analyses were also conducted. For illustration purposes, one set of elemental identification results is shown in Figure 13. The reference limits were set by the oil analysis laboratory based on historical data collected from similar wind turbine gearboxes. The six columns of analysis results correspond to reference oil samples taken from the oil drum (the left first column under analysis results), and five samples taken during the gearbox testing. If there is a component failure, some metal contents in the operational samples will exceed the reference limits, and the laboratory will notify the owner/operator of the test turbine and recommend maintenance actions.



Metals								
Iron ppm		2	<1	1	1	1	1	1
Aluminum ppm		4	<1	<1	<1	<1	<1	<1
Chromium ppm		4	<1	<1	<1	<1	<1	<1
Copper ppm		2	<1	1	1	1	1	1
Lead ppm		1	<1	1	1	1	1	1
Tin ppm		4	<1	<1	<1	<1	<1	<1
Nickel ppm		4	<1	<1	<1	<1	<1	<1
Silver ppm		4.5	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
Silicon ppm		20	<1	3	4	3	3	5
Sodium ppm			<2	<2	<2	<2	<2	<2
Boron ppm			<1	2	2	1	1	1
Zinc ppm			1	21	24	24	24	29
Phosphorus ppm			4	31	38	31	31	54
Calcium ppm			11	24	27	23	24	24
Magnesium ppm			<1	<1	<1	1	<1	<1
Barium ppm			3	8	9	6	7	7
Molybdenum ppm			<1	11	12	11	11	12
Potassium ppm			<3	<3	<3	<3	<3	<3

Figure 13: Sample Results Obtained by Oil Sample Analysis [23]

Challenges: Despite the fact that vibration analysis and oil monitoring CM techniques have been successfully applied and are increasingly deployed in the wind industry, there are still challenges which must be addressed. The very first challenge for wind turbine CM as a whole is the justification of cost benefits. The reason is that relative to traditional CM applications, the revenue stream from each wind turbine may be an order of magnitude lower. Some other challenges specific to vibration analysis and oil monitoring are discussed below.

For vibration-based CM technique, the following list can be used as a starting point for understanding the challenges [2,25]:

- Accessibility. Limited machine accessibility makes it challenging to retrofit wind turbine CM systems.
- Measurement strategy. The type, number, and location of sensors will affect the measurement and subsequently, the analysis results. In addition, the configuration of complex gearboxes varies, making it difficult to determine a cost-effective and universal solution.
- Diagnostics. Changing wind direction and speed cause variable speed and load conditions when collecting vibration data. Compared to stall-regulated wind turbines, variable speed wind turbines have additional complexities. In addition, it can be challenging to directly apply vibration-based CM systems used in other industries to the wind industry due to very low rotor speed.
- Data interpretation. Currently, a vibration-based CM system normally generates an extensive amount of vibration data which typically requires expert assistance to interpret and provide recommendations for maintenance.
- Condition-based maintenance (CBM). Online drivetrain vibration monitoring is not yet ready for CBM because there is still uncertainty about severity levels and prognostics of degradation.

To address these challenges, some recommendations for best practices need to be considered, for example:

- An individual vibration-based CM system setup for each turbine is recommended to handle the variations caused by a number of factors including sensor location, gearbox configuration, and blades condition [14].
- To handle the variation in wind and turbine operational speeds, it is important to have accurate shaft rotational speed measurement [12].

In addition, new areas of research have to be conducted, for example:

- New sensing technologies, such as the SEE sensor [14], need to be developed.
- New diagnostic algorithms, such as the synthesized synchronous sampling method [26], are needed as the standard practices may no longer be enough.

For oil monitoring, a very practical and detailed discussion was provided in [27], where the factors affecting real-time sensor readings and oil sample analyses were listed. Some of these factors can also be considered as challenges. For real-time monitoring, the challenge is to correctly interpret the real-time oil condition sensor (e.g., oil quality, moisture, and so on) readings, as operational conditions have significant impacts. This can include temperature changes that occur from stopped to running in day-to-day turbine operations and also between seasons. To mitigate this challenge, one measure proposed in [27] is to integrate speed and temperature information when interpreting the real-time oil condition sensor readings. For oil sample analysis [27], there is no single standard set for all wind turbines, as different turbine manufacturers or lubrication oil suppliers may require a unique set of analyses in order to obtain credible results. Other challenges include:

- Obtaining a representative sample. There is no access to the gearbox when a turbine is in operation.
- Inconsistent sampling practices. Oil samples might be taken at different ports and oil settling conditions for the same gearbox.
- Incomplete information in samples sent for analysis. Some missed information may include oil time, gearbox model, and oil change records.

To address these challenges, research needs to be conducted for specifying standardized tests. Education and training are needed for practices such as taking representative oil samples and proper labeling.

Future research areas: Although the CM technologies face various challenges in wind turbine applications, they are still much needed and valuable. As with any technology, there is room for improvement, so they can be better utilized to benefit the wind industry.

Based on the discussion provided in the challenges section, further research on wind turbine CM is still needed to:

- Determine the most cost-effective measurement or monitoring strategy
- Improve the accuracy and reliability of diagnostic decisions, including severity level evaluations
- Automate the “expert” in data interpretation to make actionable recommendations automatic.
- Develop reliable and accurate prognostics techniques

In addition, work is needed in the following areas:

- Improved use of Supervisory Control and Data Acquisition (SCADA) system data, which is normally only stored at 10-minute intervals
- Performance monitoring, usage monitoring, and load estimation [28] to help prognostics
- Fleet-wide condition monitoring and asset management [8]
- Root cause analysis to help improve the turbine operation, control strategy, and component design

When turbines are installed offshore, the scope of CM has to be expanded from the entire baseline onshore turbine studied here to include additional subsystems, such as undersea transmission lines. The influences of water on turbine component health need to be examined. The load estimation becomes more complex as both wave and wind influences are involved. As a result, novel sensing or sensor integration strategies [29] may need to be developed. The maintenance strategy may also need to be enhanced by integrating with improved forecasting [29].

Although these future research areas may appear challenging to address, they also represent the great opportunities for CM to shine and to help the wind industry succeed by reducing the cost of energy and increasing its competitiveness.

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