Improving reliability one blade at a time with acoustics

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Blade problems are one of the most common factors affecting continuous operation of turbines in wind farms, both onshore and offshore. Blade failures could result in not only blade loss, but damage to the turbine tower or surrounding turbines, in addition to being a safety concern for nearby populations. Sensoria looks at how reliability can be improved with the latest condition monitoring technology.

For both onshore and offshore wind turbine blades, the standard industry practice to determine blade integrity involves conducting manned or drone-based visual inspections in predetermined time intervals, usually ranging from a few months to up to three years. When structural damages are known to be present, the inspection cycle is generally shortened, which in turn is linked to reduced production and site reliability. Inspection cycles are also shortened due to the need of tracking aging problems in specific blade models.

Inspections reveal valuable information that enables damage to be located and categorized. However, association of severity to a detected defect is still not standardized. This lack of standardization means that blade OEMs, inspection companies, and special interest organizations have their own categories and damage severity definitions, with slight variations.

Capability to perform inspections is commonly associated with budgetary constraints, as well as the ability to access the turbine due to seasonality. Infrequent inspections often result in higher maintenance costs, longer downtime, poor blade performance, and in extreme cases, complete blade failure. Less frequent inspections commonly reveal an extensive list of damage, some of which, if detected at an early stage, would be simpler and less costly to repair. On the other hand, too frequent inspections can increase wind farm operational cost, reduce asset reliability, and provide a non-relevant list of damages.

To increase asset reliability and optimize maintenance and inspection costs, industries like military, aerospace and oil and gas, have adopted the use of condition-based maintenance programs to guide inspection. This method relies on the installation of several types of sensors on critical components of machines.

The goal of condition monitoring involves collecting and tracking information in a given piece of machinery to identify a significant change indicative of a developing fault. The information from the machine component or asset is used to identify when a parameter is deviating from the normal trend or when its short-term transient response is abnormal, and an inspection should be carried out.

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In wind turbines, there are mature condition monitoring systems, for instance those that focus on drive train monitoring. These systems monitor specific faults and have been commercial for decades. When it comes to condition monitoring of blades, on the other hand, the monitoring systems used are in the initial stages of development. Common sensor technologies used in condition monitoring of blades are strain gauges, accelerometers and acoustic sensors.

Each technology or sensor type has different capabilities, sensitivities and is associated with different data collection, processes and interpretation requirements. Independently of the sensor type or technology used, blade condition monitoring is complex, because of the stochastic and random nature of the loading conditions that a blade undergoes, as well as the complexity and variability between blade models and types, and the complexity and cost of instrumentation. This article focuses on the Sensoria™ wind blade monitor, based on the use of acoustic technology.

Acoustic condition monitoring using Sensoria™

Continuous monitoring technology, based on the Acoustic Emission (AE) Nondestructive Evaluation (NDE) method used by Sensoria, is a leading alternative to remotely detect blade damages including skin ruptures and perforations, cracking, delamination and disbonds caused by lightning strikes, high-energy impacts or fabrication defects. This technology has been deployed in several onshore wind sites in the US and Canada and has proven capable of detecting the presence and overtime evolution of defects affecting blades in operation.

The AE technology is based upon the following premises. Firstly, a defect/damage in a composite structure will emit an acoustic signature when the defect is stressed during operation and it grows. Secondly, certain defects like delamination and blade skin rupture are continually emitting sound, which contribute to the background noise level and its frequency content. Thirdly, impacts on a structure are detected by a cascade of dynamic and transient events that can be detected acoustically and used to alarm of its occurrence. This response is the basis of Loose Part Monitoring System commonly used in the nuclear industry.

Fourthly, the features and characteristics of the acoustic activity collected from composite structures has rich distributions of amplitudes, energies and frequencies that can be used to characterize the presence of micro and macro cracking, as well as delamination. Finally, a composite structure that has existing damage will show an increased level of activity compared to a composite structure on pristine conditions.

The sensing and data collection components form the core of the Sensoria monitoring technology. It consists of three MEMS-based AE sensors, one per blade; a data acquisition system, and a cloud-based data driven web app that serves as a graphical interface and historian. The sensors are mounted inside the blades, on the blade bulkhead and are connected to the Sensoria data acquisition system installed in the wind turbine hub. An example of a common installation in a GE 1.6 wind turbine is shown in Figure 1, where the system is installed in the hub, (Top) and the sensor installed in the blade bulkhead are shown (Bottom).

The Sensoria system pre-processes and transmits the data to the cloud via a commercial cellular network. Once in the cloud, the data processing is completed at the Sensoria Insights Data-Driven Web Application (DDWA), where tools for visualization, interpretation, blade acoustic activity ranking, alarm communication and reporting are performed.

The DDWA calculates proprietary blade grading parameters used for ranking the need to perform and prioritize inspections and follow-up based entirely on the statistical analysis of the acoustic data collected by the sensors 24/7/365. Figure 2 shows the Farm View and single turbine summary dashboard that presents both the 'Farm View' along with the Real Time Alarm (RTA) status and the single turbine summary 'Dashboard' showing both real time alarm status, current status, and historical trends of structural health proprietary quantities

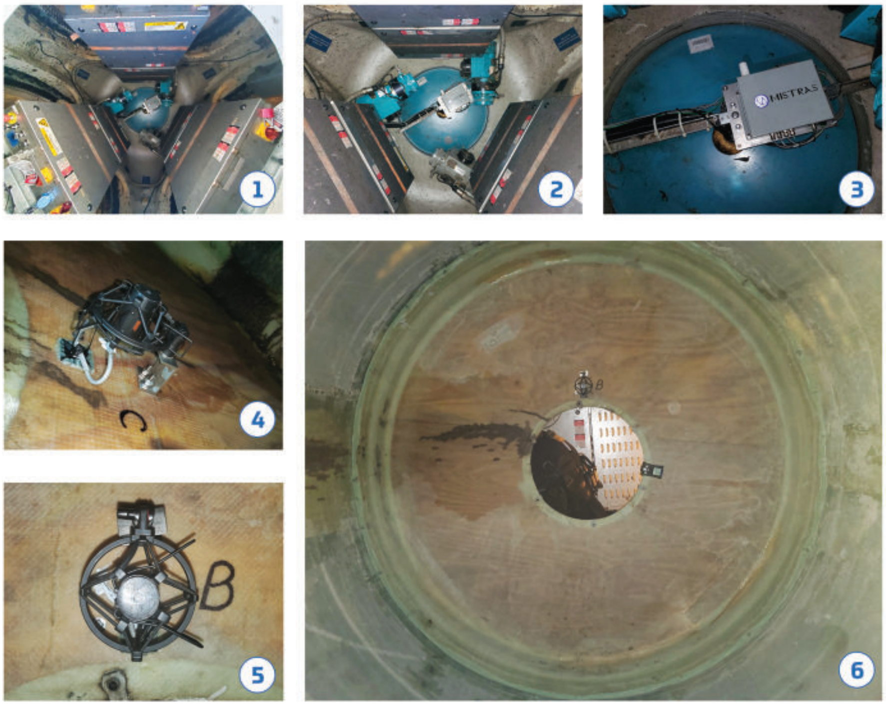

Figure 1: Example of common data acquisition system (DAQ) and acoustic sensor installation on GE 1.6 turbine. Data acquisition system is mounted on existing angle bracket (Top). Sensor is mounted on wooden bulkhead inside of the blade using a special mounting bracket and affixed with bolts (Bottom). Sensor cable is routed on the hub and connected to the system, an expansion loop to allow for blade pitch operations is used when installing the sensors

Figure 2: Selected tabs from Sensoria Data-Driven Web Application, showing the 'Farm View' with active Real Time Alarms (RTA's) and the single turbine dash-board with RTA's and the acoustic blade structural health grades: PDA and CLA

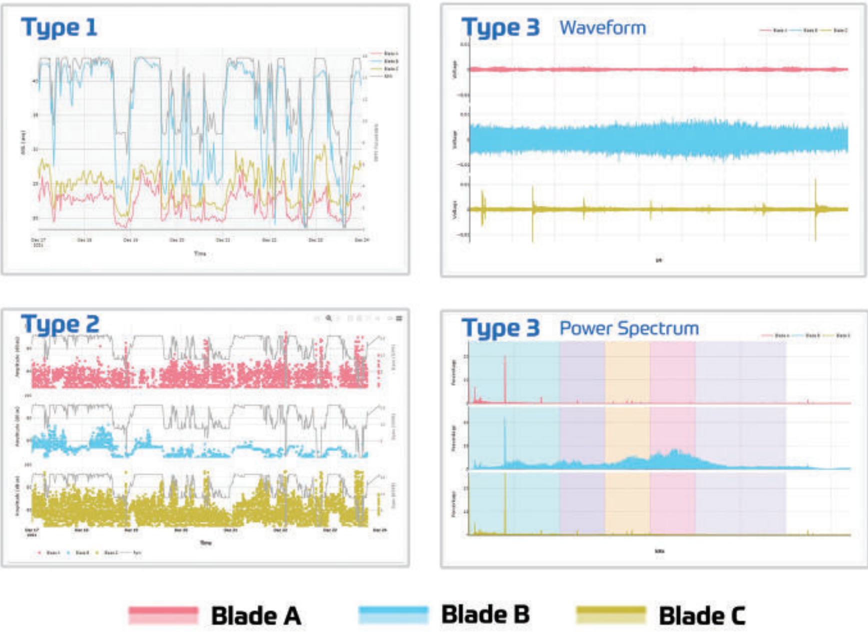

Figure 3: Types of acoustic data collected by Sensoria: 1 Continuously recorded background noise, or Average Signal Level -ASL. 2 Short-duration transient acoustic signals, or AE Hits, and 3 Long-duration acoustic signals, or streaming

used to assess the acoustic response of a blade to current operational loads.

Types of data collected and analyzed by Sensoria

The acoustic noise produced in the blade cavity is collected by the sensor installed on the blade bulkhead and processed by the DAQ in the hub or nose cone system in three different ways: Continuously recorded background noise or Average Signal Level (ASL), Short-duration transient acoustic signals or AE Hits, and Long-duration acoustic signals or steaming. An example of each type of data collected by the Sensoria sensors is shown in Figure 3.

Continuously recorded background noise (or Average Signal Level -ASL) is collected every second on each blade and averaged over time. Generally, skin perforation damages are linked to very high background noise levels and specific frequency responses. These characteristics are continuously checked on the dataset and are used to generate alarms when the background noise level of a blade has increased with respect to verified normal values or with respect to the other blades in the turbine. The average blade background noise is compared and analyzed every 30 minutes, which allows changes to be communicated rapidly.

Short-duration transient acoustic signals (or AE Hits) are recorded when crossing a pre-established threshold level. This data is used to track the onset of damage like cracks and impacts that have a transient nature. Data is collected at a high sampling rate, saved, and processed by the DAQ to determine if the activity passes or satisfies certain criteria associated with sources of noise, such as impacts, delamination and cracking. Several acoustic parameters are collected and recorded for every AE Hit passing the predetermined threshold or sensitivity. DAQ can prescreen the AE Hits collected and output alarms that are sent to the DDWA for communication and further post processing.

Long-duration acoustic signals, or streaming, recorded at pre-established time intervals is a long waveform from all three blades during a full rotor revolution. Frequency analysis of these signals is used to identify damage progression like blade skin rupture and to find any changes in the background noise of each blade. These signals are used to automatically verify changes in the background noise before and after an alarm from the AE Hit data is detected. For instance, this logic is used to identify the occurrence of an impact or lighting strike strong enough to rupture the blade skin.

Analysis procedures, which involve combination of data types, cross-referencing data trends, and changes among these are important for signature verification and to reduce the possibility of false alarms. Sensoria's DDWA runs post processing algorithms in the background that combine and correlate the different data sets collected per blade; it also compares the responses among all three blades in the turbine, and an 'expected' response derived from tracking healthy blades under several months of operation.

As an example, Figure 4 shows the changes in the streaming and background noise response of a blade running with a trailing edge crack before and after the blade was repaired. This figure shows the comparison of the background noise per blade when the trailing edge crack was present and after it was repaired. The figure also shows (top right) the comparison of the frequency spectrum collected before and after the crack was

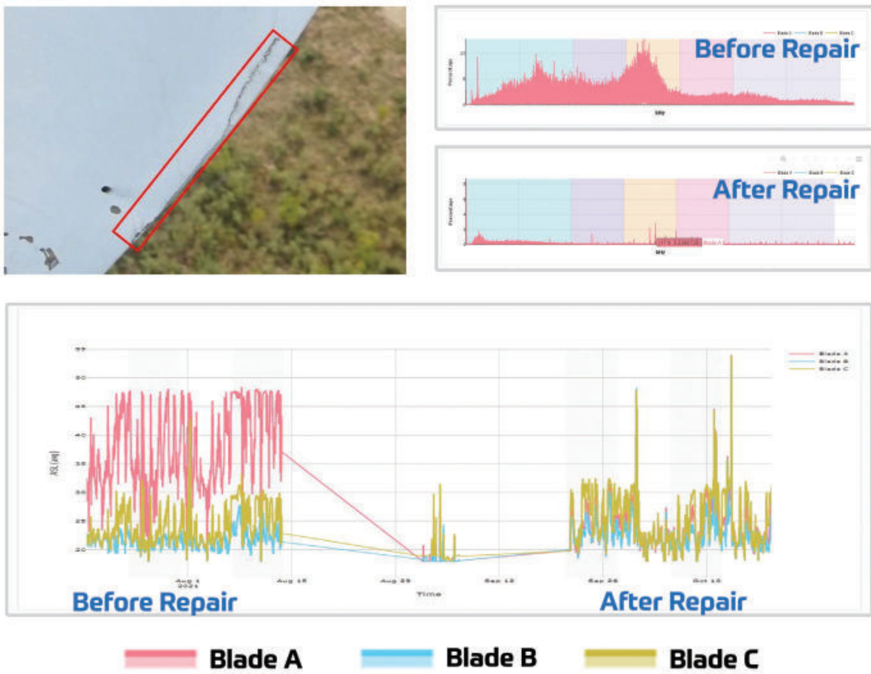

Figure 4: Acoustic background noise and frequency response of the streaming waveform collected before and after a trailing edge crack repair. Top left shows a drone picture of the blade damage in blade A. Top right shows representative streaming or long waves collected before and after repairing the damage. The bottom plot shows the background noise of all 3 blades in the turbine showing few days before and after the damage repair. This pot shows the change in the trend of Blade A before and after the repair

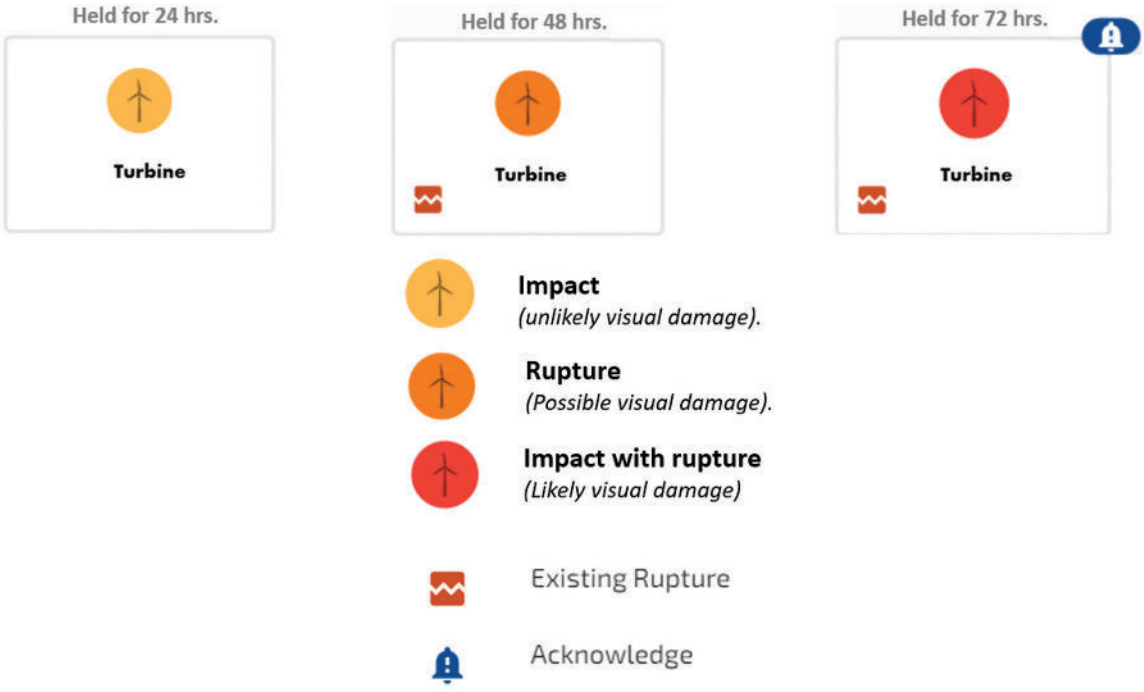

Figure 5: Real Time Alarm (RTA) nomenclature and graphical representation as it appears on the Sensoria Data-Driven Web Application 'Farm View' screen. An example of these alarms and status is also shown in Figure 2

repaired, indicating the difference in the signature due to the presence of the damage.

Real time alarms

One of the objectives of monitoring wind rotor blades is to use the data continuously collected by the Sensoria system to generate Real Time Alarms (RTA). These identify when the acoustic behavior of a blade deviates from expected variations related to normal wind turbine operation.

To date, Sensoria has three RTA alarms implemented; impact no rupture, skin rupture, and impact & skin rupture. Communication of an alarm is done via email to a predefined group of personnel, including Sensoria's highly trained team of analysts. The first type of alarm can be communicated within one hour of occurrence, and is resolved at the instrument level using the AE Hit data or short transient acoustic signals.

Communicating a possible blade skin rupture requires comparison of the current background noise response with the previous data point and the next data point. This past and future comparison is used to verify that the condition or change is sustained over time.

This comparison is performed by contrasting the continuously recorded background noise (or ASL) and the frequency response of the streaming data or long duration acoustic signals collected a minimum of three times a day. Finally, an alarm is produced when conditions in items one and two are met within a small-time window, indicating that an energetic impact was linked to a blade skin rupture.

The Data-Driven Web Application provides a farm or site level view, where the user can graphically see any relevant active alarms or heightened status and add certain icons to the turbine tile showing the need of the user to acknowledge the presence of an alarm, as well as the existence of a previously detected blade skin rupture (see Figure 5).

Occurrence of any alarm is saved into the turbine database and the history can be easily accessed by the user, as well as filtered depending on alarm date and type. Alarm icons remain active and displayed for a predetermined period of time, and more drastic events are visible for longer time periods before the status is cleared.

Blade structural health grading

Structural health or integrity of an asset, machine or structure refers to its ability to sustain the operation that it was designed for. Asset operation is linked to wear and tear and having a way to determine its health status and the remaining life span is highly priced in current times where high reliability is expected.

Sensoria uses the acoustic signatures of wind turbine blades to grade structural health of blades and support asset owners in the prioritization of asset inspection and supplies information between inspections to better manage asset operation. Detection of damage onset and evolution is done by tracking over time transient and dynamic changes in acoustic signatures from the blades. Sensoria offers a proprietary blade grading system that allows comparison among turbines and blades in the site or wind farm.

The grading system can ultimately be used to rank the blades depending on their acoustic signatures. Two important proprietary quantities have been developed for this purpose; Crack-Like Activity or CLA and Probability of Defect Activity or PDA.

Crack-Like Activity or CLA is calculated based on a crack filter developed by tracking the acoustic characteristic of a group of blades with cracks confirmed by inspections over a period of several months. Its value is a number between 0 and 100 with higher values showing a higher percentage blade acoustic activity satisfying the crack filter conditions over a pre-established time period.

The CLA filter was developed using 30 blades, 10 of which had cracks, with a severity from 2 to 4, documented from an inspection performed by rope access or drone before the monitoring started. The filter is used to identify the level of signatures satisfying known signal behaviors present in a dataset when cracks are present on a composite structure and growing.

Probability of Defect Activity of a blade is a percentage number that represents actively growing damage, and its magnitude is related to the detection of acoustic defect activity. The PDA weekly calculation considers several acoustic features associated with specific defects activity, such as cracks, delamination, and blade skin ruptures. High PDA values indicate the presence of

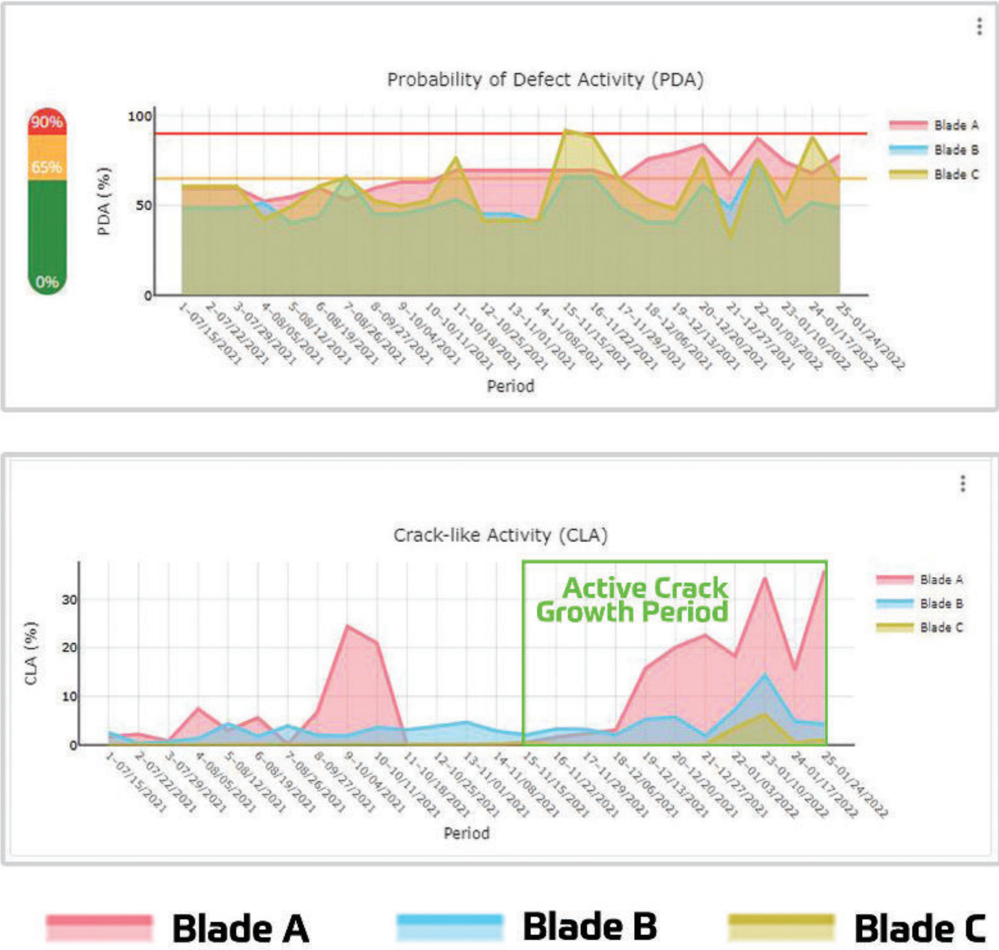

Figure 6: PDA and CLA of a wind turbine between inspection cycles. Blade A shows CLA, and latest inspection corroborated the appearance of a chord crack on the blade around 40m from the root

abnormal spikes in acoustic activity, changes in acoustic trends, or deviations from normal behavior. PDA is calculated and displayed in the DDWA. Blade PDA value varies over time in response to turbine operation and weather, because these factors affect the mechanical load on the blade and therefore the acoustic activity collected by the sensors. Tracking PDA for every blade over time and comparing it with other blades in the same turbine or the blade population in a wind farm allows us to rank the blades from worst to best, and to identify which blades the inspection and repair resources should be focused on with higher priority.

These quantities are calculated on a weekly basis, as that time period enables the collection of information of the wind turbine operating through a statistically significant sample of rotor speeds and through a wide range of wind speeds. Therefore relevant comparison between blades of the different turbines in the site or wind farm can be made.

Figure 6 shows the PDA and CLA quantities for a turbine for over a year and in between inspection cycles. This turbine started showing high CLA activity on Blade A in early August 2021. Inspection in October 2021 showed the presence of a new crack, not seen during the previous inspection in September 2020. The CLA plot shows periods of activity and periods of inactivity when the crack is not growing. Such a dynamic response is commonly seen acoustically in composite structures and materials. In addition, the PDA plot shows a trend increasing steadily, even in periods where the CLA is low, highlighting the need for a follow up inspection.

Guiding inspections, maintenance and improving reliability

Knowing the moment that new damage on a wind turbine blade occurs or existing damage is showing signs of activity, helps guide the next steps and to better prioritize and manage complex schedules. Knowing if a new damage on a blade occurs or if the acoustic response of a blade with known critical defects dramatically changes between scheduled inspections, can be used to prioritize repair and inspection. Through the use of structural health grading parameters derived from acoustic activity, Sensoria can be used as a tool to plan and manage resources to improve site reliability. Combining information for real time alarms, PDA and CLA a ranked list of blades that require more urgent inspection and follow up can be generated.

Conclusions

The use of remote continuous monitoring of wind turbine blades based on AE provides early information about the onset and evolution of damage. Blade damages inhibit energy-generating capacity, particularly when they worsen after onset.

Knowing the condition of every blade when compared with the blade population of a wind site allows for proactive planning of inspections and repairs, thus reducing repair cost and risk of unexpected blade failure.

As wind energy utilization continues to expand globally, the quantity of blades will increase worldwide, and blades already in operation will continue to age, making real-time condition monitoring a crucial aspect to operational efficiencies and maximization of uptime. Remote blade monitoring is a logical evolution in blade integrity management best practices as the industry seeks to exponentially scale up to meet growing global demand.

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