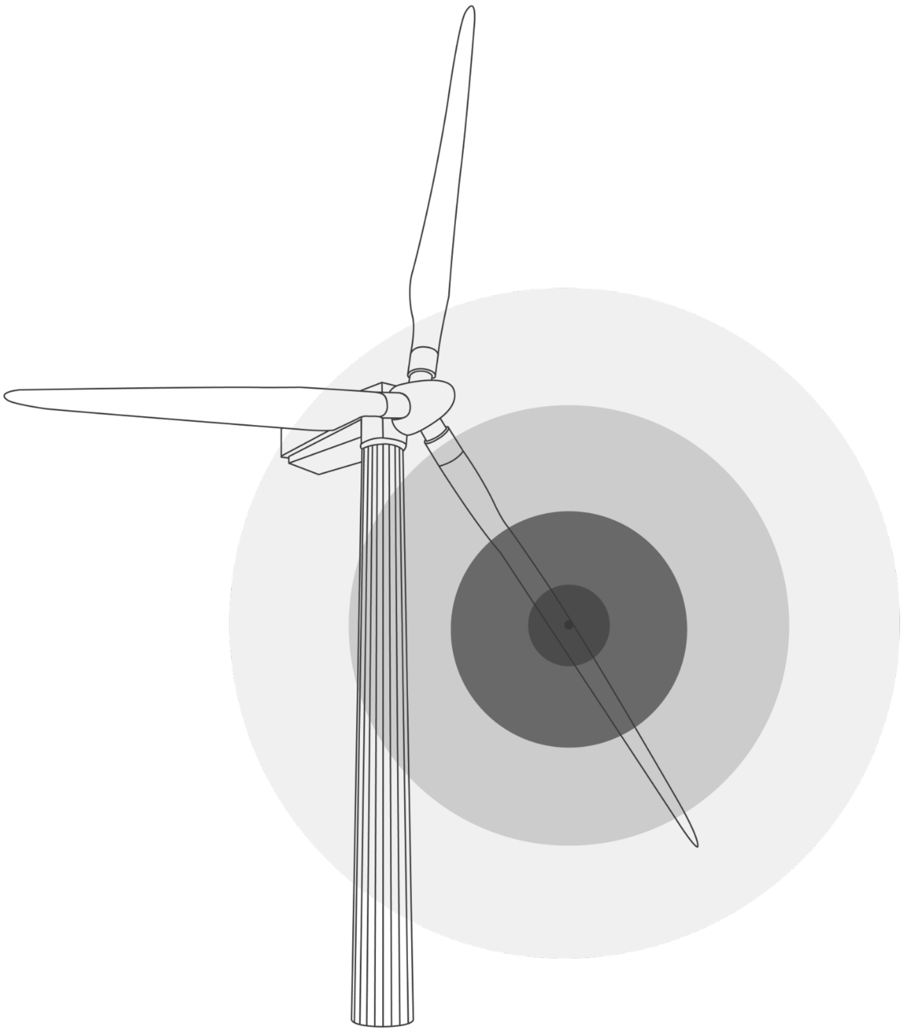
Ping Monitor

Continuous Non-Contact Blade Damage Detection

SYSTEM OVERVIEW AND RESULTS



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1. Introduction

The aim of this paper is to provide general background information on the Ping Monitor system set-up and operation, and to present results from several test sites.

The Ping Monitor is a device that continually monitors the health of wind turbine blades and automatically sends alerts to maintenance staff when a change in the level of blade damage is detected.

The Ping Monitor is placed permanently at or near the base of a wind turbine, continuously listens to noise from the wind turbine and detects damage based on the subtle difference in sound generated by damaged blades when compared to healthy undamaged ones.

It is powered by a solar panel and uses satellite communications to send blade health information and alerts to maintenance personnel when blade damage is detected. The continuous monitoring of a wind turbine's blade health brings several benefits to the wind farm operator:

- The ability to perform early maintenance work to stop the progress of minor defects to major defects.
- Significantly reduce the risk of late and costly repair or blade replacement.
- An overall simplification of blade repair work and an overall reduction in maintenance costs.

Figure 1 - The Ping Monitor installed on a wind turbine with magnet mounts

2. Background

2.1. The issue and current industry approach

The demand to increase the output of wind turbines in recent years, has driven the design of larger turbine rotors and blades.

Larger turbine blades are subjected to greater bending moments and structural stresses. To maximise the return on investment, focus is placed in optimising blade construction by minimising material and weight. Such objectives can potentially come at the cost of blade design safety margins.

The increased size of wind turbine blades also translates into a greater total blade surface area. With a greater surface area, the likelihood of more surface defects increases.

The rotor blade has a relatively large failure frequency compared with other elements; at around 23% of the total number of turbine breakdowns. Operation and maintenance (O&M) have been shown to contribute to around 25% to 30% of the total costs of offshore wind power.

The current turbine blade maintenance approach is to repair damage if necessary. Repairs are carried out following an annual survey of the rotor blades, which are undertaken through visual means using drones, ground based cameras or rope access.

This approach is sufficient when damage propagates slowly, however, some damage can propagate rapidly. The late detection of damage propagation can result at best in expensive major repairs and at worst blade replacement or blade failure leading to both large scale repair costs and power generation loss due to extended downtime.

Condition monitoring is widely used in the wind turbine industry to predict and reduce the risk of failures in rotating components such as bearings, gear boxes and generators. There is however currently no widely adopted method to continuously monitor the health of wind turbine blades. The Ping Monitor provides a solution for continuous condition monitoring of wind turbine blades opening the door to timely detection of damage so less costly turbine blade repairs.

Preventative maintenance of turbine blades provides the potential to predict a blade's life span to support O&M decisions and avoid major failure events. Operators of large wind farm with thousands of turbines are looking for solutions to reduce costs and concurrently increase turbine efficiencies.

2.2. Damage detection technology

The Ping Monitor measures sound to detect damage from wind turbine blades. The idea for the Ping Monitor stems from the experience of maintenance personnel in the field who sometimes noticed changes in the sound generated by damaged blades.

Figure 2 shows two examples of acoustic signals that were measured from two wind turbines, one with blade damage and a second one without blade damage. These signals illustrate a clear difference in the acoustic signature generated by two otherwise identical turbines operating under the same wind conditions.

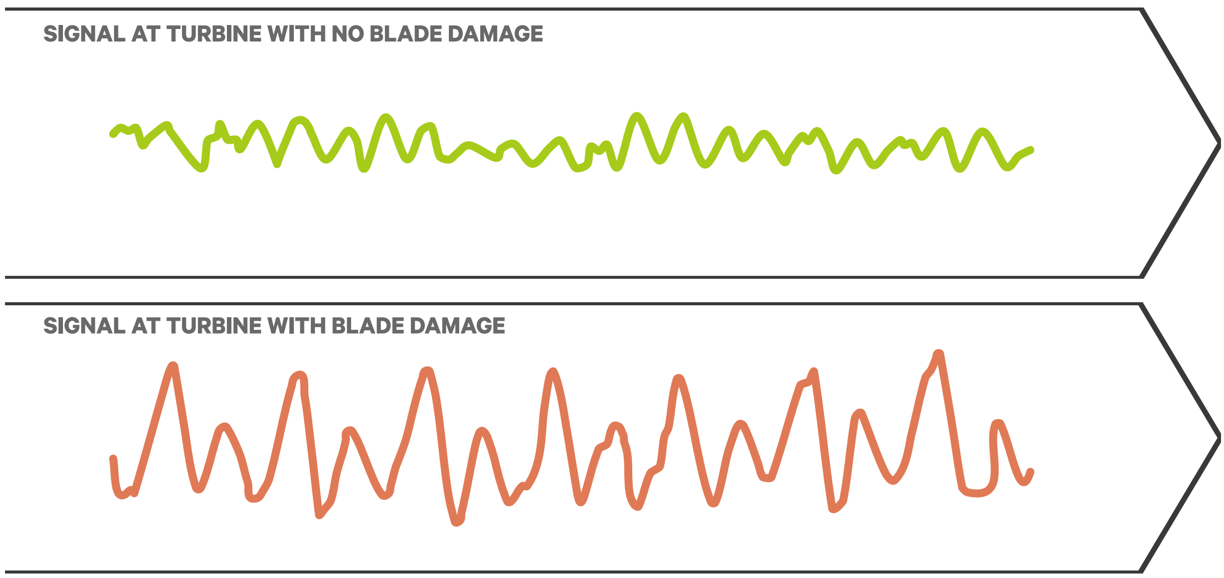
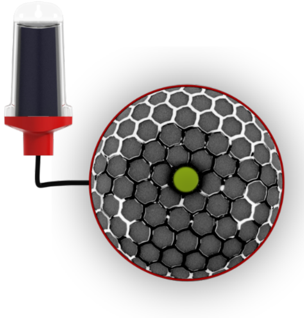


Figure 2 - Example acoustic signals recorded at two otherwise identical wind turbines

There are several mechanisms through which sound can be generated by damage on the wind turbine blade. These include:

- Irregularities and disruptions on the blade's surface which generate noise as the air moves rapidly over the blade surface.
- Holes through the blade skin, which can generate a whistling type noise due to the air rushing through them (a result of the centrifugal force on the air within the blade).
- Crack movements, which may cause rubbing and or creaking as the blade load changes with every rotation.
- Regardless of which of the above mechanisms is creating the noise, the sound from the defects is detected by the Ping Monitor located at ground level in the vicinity of the base of the wind turbine.

The key proprietary algorithms available in the Ping Monitor were developed specifically to discriminate between noise caused by damaged blades and noise in the general environment. As a result, the monitor can operate without any reduction in performance at sites where intermittent noise from for example livestock, vehicles, aircraft, birds and wind gusting through vegetation are present.



An advantage of the use of sound to detect blade damage is that it is possible to use a single sensor location on the ground to detect the damage, rather than instrumenting each individual blade with multiple sensors. This provides a reduction in the costs of both the data acquisition hardware and site installation.

The advantage of being able to continuously survey the whole turbine, through use of sound and a single low-cost sensor does make it more challenging to determine exactly where on the turbine that the defect is located.

Because of this, at the present time the Ping Monitor will not completely replace the use of visual inspection techniques.

It is expected that the monitor will provide a tool which continuously monitors a turbine and identifies when the need for further investigation is required such as a basic visual inspection by site staff from the ground or imagery by drone. A visual inspection following a Ping Monitor damage detection alert would confirm the urgency and the best repair course of action. In cases where a repair is not immediately warranted, the Ping Monitor will continue to monitor the defect, tracking its progression over time.

While the starting point for the Ping Monitor was the ability of site staff to hear some defects on wind turbine blades, the development of the monitor has today reached the point where the system is able to detect damage far quieter than is noticeable by an experienced listener standing at the base of a wind turbine.

An international patent has been filed to protect the Ping Monitor under the Patent Cooperation Treaty (PCT).

3. System outline

Figure 3 provides an outline of the Ping Monitor operation, with further detail provided in the following sections.

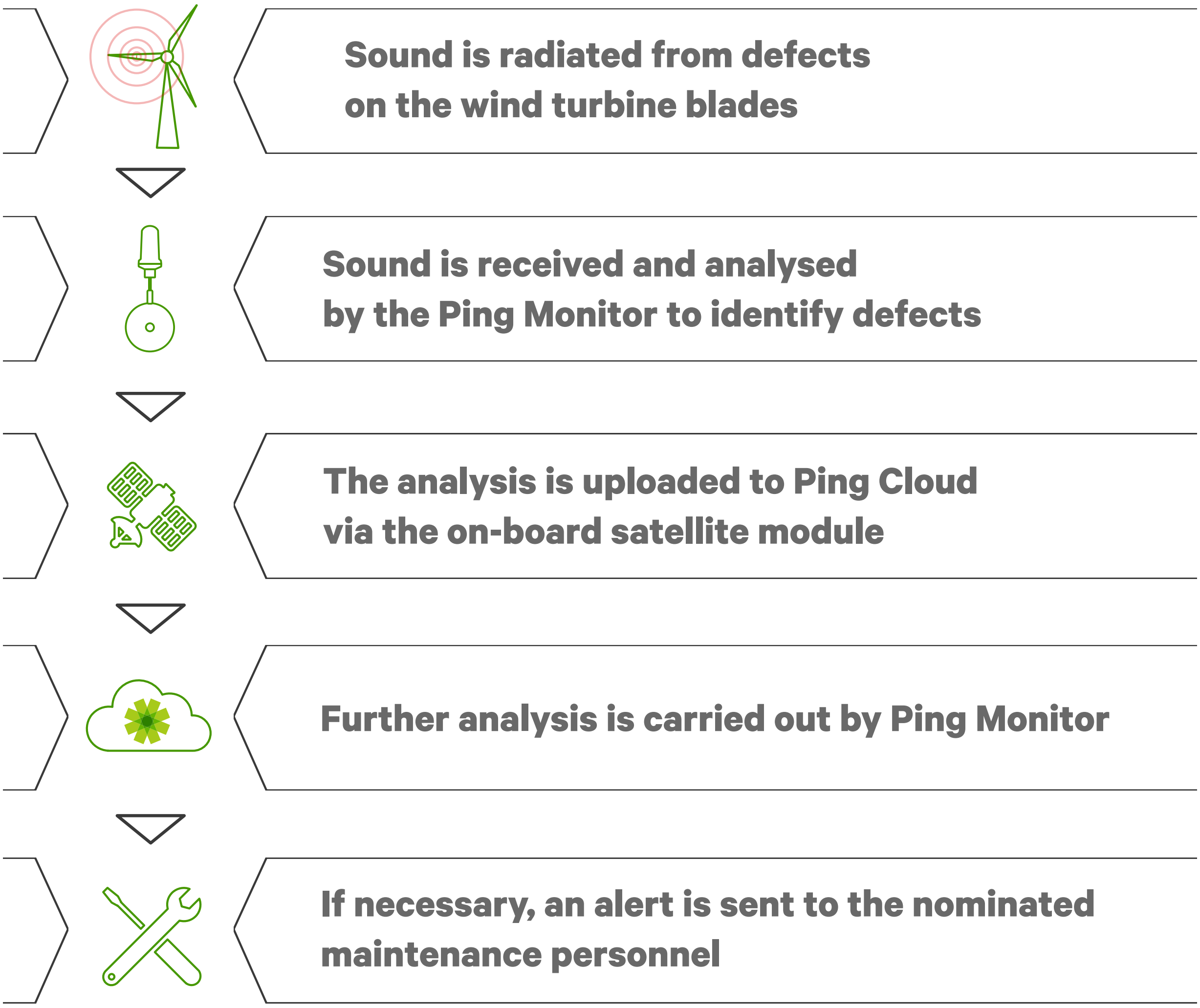


Figure 3 - Outline of the Ping Monitor operation

3.1. Ping Monitor hardware

The Ping Monitor hardware consists of an outer replaceable wind shield, inner housing which contains the microphone and other electronics, and a base board. The wind shield is an inverted conical shape, with a base diameter of 300mm, and height of approximately 250mm. A picture of the hardware can be found in Figure 1.

The housing has been designed to protect the microphone and electronics from rain, strong winds, sheds debris and other environmental contaminants.

3.1.1. Solar power

The Ping Monitor was designed with low power components and as such the system can be powered continuously via a small solar panel. The panel is attached to the base of the unit and has been sized to operate in Northern European regions. The monitor is also equipped with onboard lithium-ion battery pack with enough capacity to power the monitor for several weeks without any direct solar charge.

3.1.2. Satellite communications

Ping Monitor uses satellite communications to transmit turbine blade health information to the cloud-based service, Ping Cloud, which alerts maintenance personnel when blade damage is detected. Satellite communication was selected as the means of communication with the device for the following reasons:

- It offers more reliable communication links when compared to ground-based telecommunications network (3G, 4G, LTE), especially in rural areas where wind turbines may be located.
- It does not require the need to setup and use a variety of telecommunications network providers, an advantage particularly for installations across international sites.
- It does not require the need for complicated localised ground based wireless networks.

While satellite communication has historically been cost prohibitive, recent advances in technology have reduced the cost to the point where it competes well against the other potential data transmission options, particularly when ease of setup and use is considered.

3.2. Ping Monitor analytics

Sound from the damaged wind turbine blade is received by the microphone located in the centre of the housing. This sound is processed through several algorithms to identify noise which is attributable to blade defects, and exclude other environmental noise, such as noise from livestock, birds, insects, vehicles and wind blowing through vegetation.

Noise classified as resulting from blade defects is further processed to produce several metrics. These metrics provide information on the type and severity of the damage detected. The outcomes of this assessment are then transmitted to the Ping Cloud via the on-board satellite communication module.

3.3. Ping Cloud

The Ping Cloud server receives the metric data generated by the Ping Monitor located at each turbine in the field. Further analysis of this data is then undertaken by the Ping Cloud to determine the overall blade health. Additionally, ping cloud performs trend analysis of the blade condition over time comparisons between other similar turbines, allowing the operator to prioritise repairs as required. Once an issue with a wind turbine blade is identified an alert is sent from the Ping Cloud to the nominated maintenance personnel advising that an action or further investigation is required.

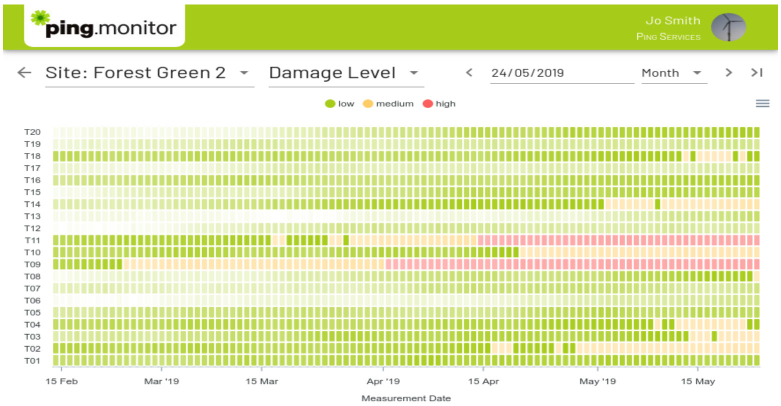


Figure 4 - Ping Cloud, comparison of turbines and tracking over time

Ping Cloud provides maintenance supervisors with a visualisation of the trending and comparison of turbine damage at a turbine, site and fleet wide level.

Two example screen shots from the Ping Cloud are provided in Figures 4 and Figure 5.

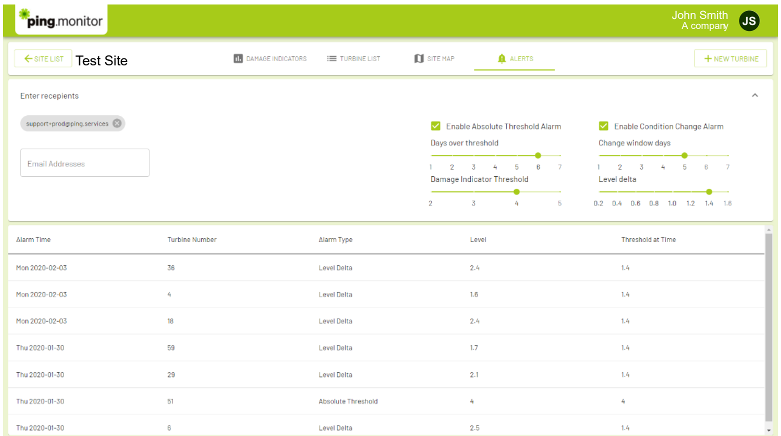
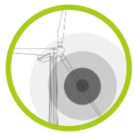
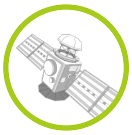


Figure 5 - Ping Cloud, alarms & alerts User Interface

Blade Condition Monitoring





Anywhere

Continuously

3.4. Installation

The Ping Monitor is available in either a tower mount or pole mount version. One monitor per wind turbine is required.

The tower mount version is fitted with a quick mount magnetic bracket, allowing for the Ping Monitor to be placed directly on the side of a steel wind turbine tower. The pole mount version is normally installed approximately 30 m from the base of the tower, and is provided with a bracket that allows for the unit to be fixed to the top of a fence post, star picket, or similar.

The main advantage of the magnetic tower mount version is the ease of installation. The advantages of the pole mount version are the Ping Monitor's greater sensitivity to defects (particularly on the front of the blades near the root) and the ability to move away from noisy transformers or cooling systems at the base of the tower if they are present.

The Ping Monitor is installed at a height of 1m to 4m above ground level. The installation height does not influence the effectiveness of the system and it is selected on a site by site basis, considering the following factors:

- Ease of access for installation and maintenance if required.
- Security against theft.
- Likelihood of livestock or wildlife damaging the equipment.

As a result of the use of solar power and satellite communications, the monitor requires no connection to site services (power or data).

3.5. Maintenance

The Ping Monitor wind shield and solar panel are the only parts likely to require maintenance or replacement.

The wind shield cover is made of a UV resistant fabric. As the cover is directly exposed to the elements, the fabric will degrade over time and a replacement will be required after several years. The wind shield is stretched over the monitor and held in place by a single drawstring and can be easily replaced by site personnel. The Ping Monitor is able to monitor the condition of the wind shield and generates an alert when a replacement is required.

The Ping Monitor also tracks battery voltage and will generate an alert if insufficient power is not regularly being provided by the solar panel (for example due to dirt build up or bird fouling on the panel).

No other regular maintenance or on-site intervention is likely to be required.

4. Results

This section presents some of the results that have been gathered to date using the Ping Monitor system.

The Ping Monitor has been deployed at more than a dozen wind farm sites, in Australia, the USA and Europe. The monitor has been shown to require no adjustment or fine tuning to work on the different models of modern horizontal axis wind turbines that have been evaluated to date.

4.1. Types of damage detected

The Ping Monitor analyses the sound that is detected from the blades to identify whether the sound is abnormal. It then compares this sound with previously known acoustic signatures from damaged blades to help identify the likely magnitude and type of damage. At the present time it is not always possible to determine the type of damage on the blades, however, the classification of damage type is a current focus of research and development activities and is constantly improving.

The following types of blade damage and defects have been detected by the system to date:

- Root cracks
- Cord cracks
- Surface delamination
- Leading edge erosion
- Tears in leading edge protection tape
- Holes
- Split tips
- Lightning damage

The photos in Figure 6 show some of the defect types detected by the Ping Monitor.

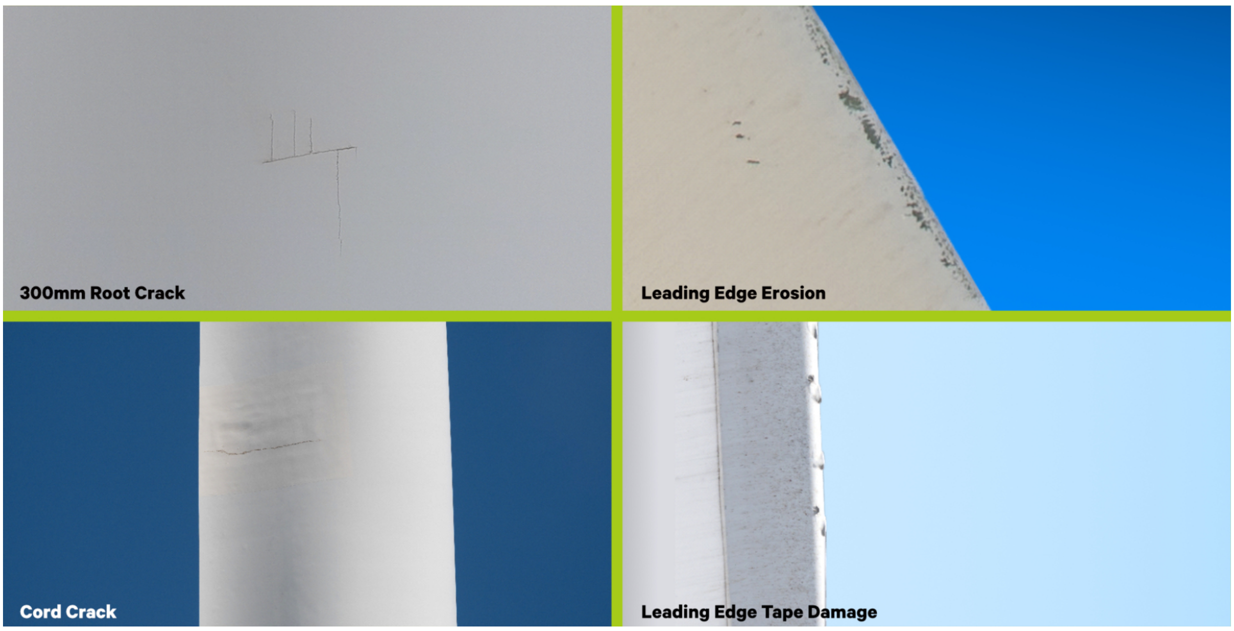


Figure 6 - Photos of some of the damage detected using the Ping Monitor.

4.2. Trial at research turbine

A trial was conducted with a wind turbine OEM using a turbine reserved for research studies. The objective of these tests was to confirm the types of damage the Ping Monitor can detect. The use of the research turbine afforded the Ping Monitor team the flexibility to make blade modifications to test the types and level of damage detectable by the system.

Prior to the Ping Monitor team arrival on site, it was believed that the blades were in relatively good condition. However, the initial baseline study prior to any blade modifications identified several defects. As a result, during the first week, the study focused on improving the condition of the existing blades. The repairs were made progressively rather than all at once, thus allowing for acoustic measurements to be taken once a defect was repaired. These defects included bent serrated trailing edges, tears in leading edge protection tape, a damaged lightning detector, pitot tubes and loose objects inside one of the blades.

In the second part of the study, small holes on the surface (25 mm diameter), and a 500mm long scratch at 19 m from the root (to simulate a root crack) were assessed.

In all, a total of seven unique states of blade damage were assessed, and the Ping Monitor successfully distinguished the difference between all of the blade damage conditions tested.

During the time on site, there was a period of approximately 24 hrs during which the test turbine blades iced up. The periods of turbine icing were evident in the acoustic data gathered. At this stage an algorithm to automatically detect and flag turbine icing is yet to be developed, however, it is expected this will be possible through the acquisition of data from further instances of wind turbine icing.

4.3. Detection of root cracks

Tests to confirm the ability of the Ping Monitor to detect root cracks have been conducted. Root cracks are a more challenging type of damage to detect, due to the typically relatively minor surface damage and the proximity of such damage to the hub where the blade speed is significantly lower.

In a “blind” trial of the Ping Monitor, the test site owner made available six wind turbines for testing without providing any prior information about which turbine already presented root crack damage. Two of the turbines had relatively significant damage, however, not so severe to render the turbines inoperable. Two of the turbines had relatively minor root crack damage, but still required repair. The remaining two turbines had no known damage. The Ping Monitor team were asked to identify which of these turbines were most damaged.

The root cracks on the tested turbines were all at approximately 10 m from the hub, with internal delamination sizes of between 300 mm and 500 mm. A photograph of the external blade surface damage from one of the root cracks is shown in Figure 6.

The Ping Monitor successfully identified which of the turbines had the most, least, and no damage. A plot showing the relationship between the blade damage detected and the size of the internal delamination of the root cracks is provided in Figure 7.

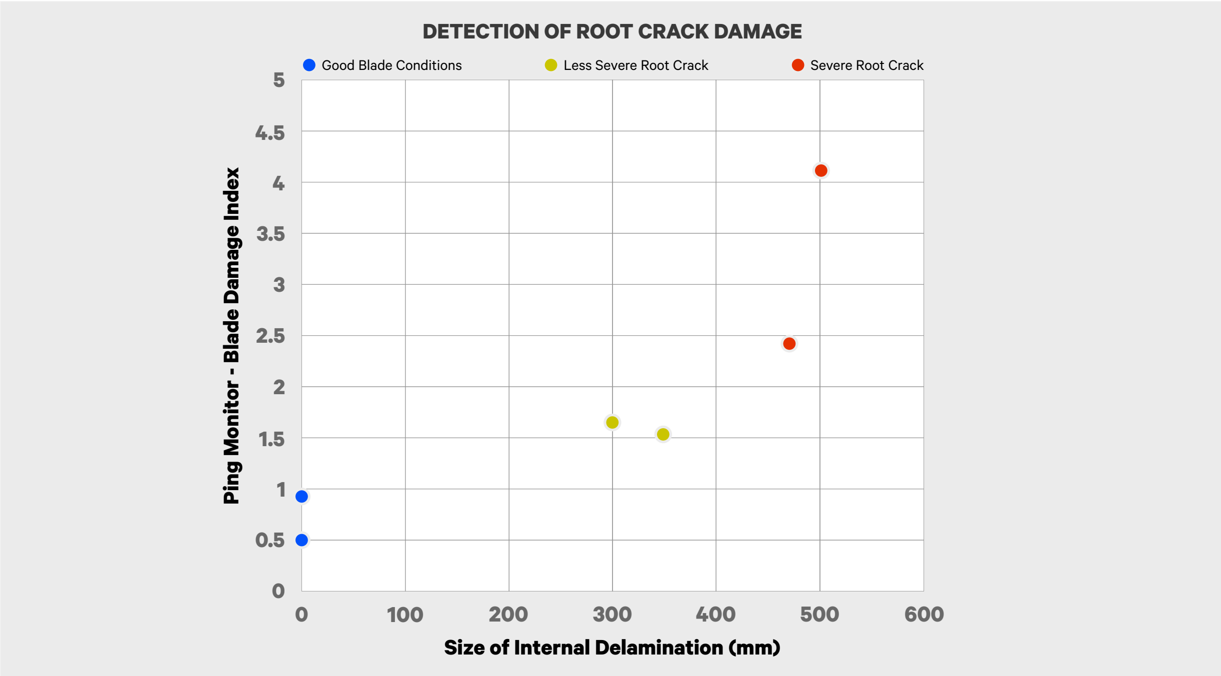


Figure 7 - Relationship between actual damage size and damage severity detected using the Ping Monitor

From the graph in Figure 7 it can be seen that minimal blade damage was detected at the two turbines with blades in good condition while the most significant damage was detected for the two turbines with greatest level of root crack damage.

4.4. Early correlation studies

As part of the Ping Monitor continuous improvement and refinement of the damage detection ranking algorithm, a detailed correlation between Ping Monitor measurements and current industry standard visual defect ranking is on-going. Early results show promising correlation between Ping Monitor and trial site inspection data sets. More analysis is progressing at the time of writing.

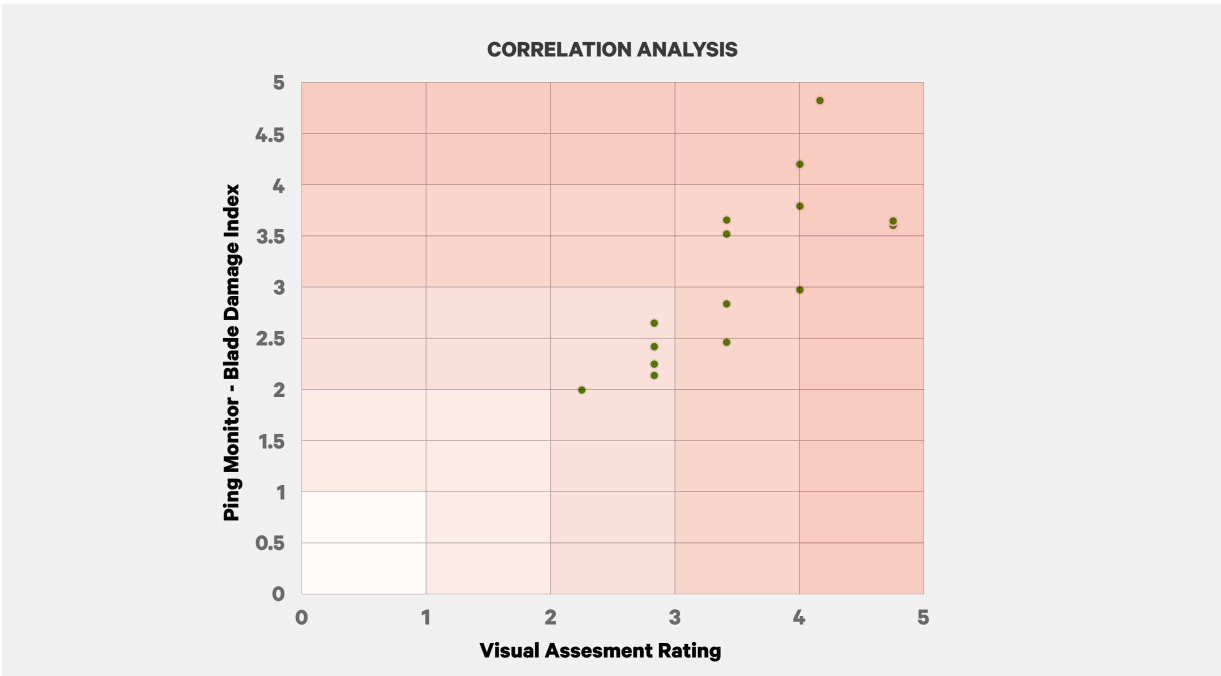


Figure 8 - Early Correlation analysis between Ping Monitor and Visual inspection data

5. Summary

The Ping Monitor has been developed to continually monitor the health of wind turbines blades and alert maintenance staff when blade damage is present.

The monitor is powered by a solar panel and uses satellite communications to send blade health information, thus requiring minimal ongoing maintenance.

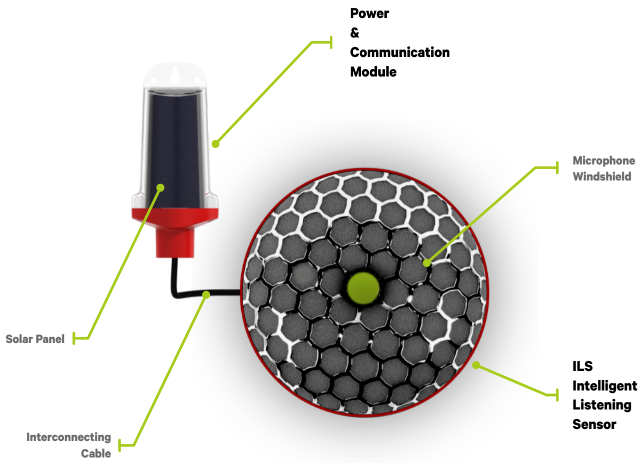
The monitor can detect a range of damage types, including but not limited to root cracks, cord cracks, leading edge erosion, tears in leading edge protection tape, holes, split tips and lightning damage.

The ongoing continuous monitoring of wind turbine blade acoustic health allows for earlier maintenance avoiding minor defects progressing to major defects requiring costly repairs or blade replacement. As a result, the Ping Monitor assists in early preventative maintenance that in turn simplifies blade repair and reduces the overall maintenance costs.

6. Ongoing Research & Development

The Ping Monitor hardware and analysis algorithms are following a continuous research and development road map. At the time of writing a third generation hardware and additional algorithms are being developed and finalised.

To further provide user operational flexibility, in addition to Satellite IoT communications, protocols such as LTE CAT-M1, NBiOT and LoRaWAN options are being considered and implemented.



Upcoming Ping Monitor Intelligent Listening Sensor (ILS) housing and packaging revisions will further enhance the system.

Intelligent
Listening

Ping Services
Suite 28
Stone & Chalk, Allied Health Building
Lot Fourteen, North Terrace, Adelaide SA 5000

E: info@ping.services
W: pingmonitor.co