BACKGROUND

RNRG worked with a large wind turbine owner in North America to demonstrate that the TurbinePhD™ condition monitoring system can detect faults early and reduce maintenance costs. An evaluation program was implemented that ensured the owner would be able to see the fault detection value of TurbinePhD with minimal investment of time and capital. The owner selected three multi-megawatt wind turbines on the same wind farm; two of the turbines had no faults, while the third had a fault somewhere in the drivetrain. The fault was one the owner normally saw on this type of turbine. It was a blind trial, so Renewable NRG Systems installed the TurbinePhD systems on the selected turbines without knowledge of which turbine had a faulted component or whether the faulted component was a bearing, shaft, or gear.

OBJECTIVE

TurbinePhD is designed to identify faulted components early so that proactive maintenance actions can be performed, reducing the cost of repair. To enable this cost reduction, it is critical to detect faults before the damage on one component causes secondary damage on other components in the drivetrain. Secondary damage occurs when wear debris from the initial fault is carried by the oil into other components, where it is over-rolled creating a dent and starting a new fault.

In addition to early fault detection, it is important that users are able to quickly determine if there is a faulted component without needing to analyze vibration waveforms or frequency spectrum. TurbinePhD combines advanced vibration processing techniques leveraged from the rotorcraft industry with a patented automated diagnosis capability to accomplish this. The web-based user interface then displays the health of all the turbines using a traffic light display.

![Figure 1](image.png)

*Figure 1. Bearing rolling elements create impacts when the pass over damage on the bearing races, creating a periodic series of impacts through time.*
SOLUTION

Since the value of a condition monitoring system is based on the accuracy and timeliness of the diagnoses it produces, not the amount of vibration waveforms it captures, this case study focuses on TurbinePhD’s analysis capability and how it determines the health of each turbine using an example of a high speed bearing fault detected in the field. TurbinePhD’s analysis capability can be broken into two components: the advanced vibration processing techniques and the patented automated diagnosis capability.

Advanced Vibration Processing

Unfaulted bearings allow for low friction transfer of power and create very little vibration. The rolling elements are separated from the inner and outer bearing races (see Figure 2) by a layer of lubricating oil; ideally there is no direct contact between the rolling elements and races. When a fault is initiated, the lubricating layer is lost and contact between the rolling elements and bearing race occurs. The fault could be a dent from over-rolling of particle contamination, spalling from fatigue, pitting from electrostatic discharge (generator), corrosion from water contamination, or a crack on the bearing race. Regardless of the type of fault, the vibration signature it creates is similar. Every time a rolling element passes over a fault it creates an impact, much like a car tire hitting a pothole. Since there are many rolling elements in the bearing, there are many impacts created during one revolution of the shaft. When detecting a bearing fault it is this vibration caused by these impacts that is used to detect the damage.

The spacing between the impacts is dictated by two factors: the speed at which the bearing is rotating and the physical distance between the rolling elements. This repeating set of impacts excites resonance in the gearbox or generator casing – causing it to vibrate. The timing between the impacts changes depending on whether the fault is on the outer race, the inner race, or the rolling element itself. Therefore, if the speed of the shaft is measured and the geometry of the bearing is known, one can determine the frequency of the impacts that each of these faults will cause.
To detect these potential bearing faults, the bearing envelope analysis technique is used. First the raw vibration signal is filtered so that the bearing fault signal is isolated. Selecting the correct filtering method is critical, since the bearing vibration is much smaller than that of the gear meshes. For bearing faults, it is only the frequency of the impacts that provide fault information, so the envelope of the filtered signal is taken. While there are several ways to accomplish this, all of the methods calculate the modulation (or “profile” in more basic terms) of the filtered signal (see Figure 3). The Fourier transform of the enveloped signal is then taken, creating a frequency spectrum to determine if there is a repetitive signal indicative of a bearing fault. Distinct fault frequencies can be seen in the frequency spectrum if a bearing fault exists.

For each vibration acquisition taken, the amplitude of all the bearing fault frequencies is calculated, resulting in a scalar value referred to as a condition indicator. Each of the condition indicators tracks a particular fault mode of the component being monitored. For bearings, this includes the amplitudes of the bearing fault frequencies (outer race energy, inner race energy, ball energy, and cage energy) as well as other values.

Figure 4 shows an actual envelope frequency spectrum taken from the TurbinePhD website for the faulted high speed bearing. The fault frequencies are visually marked using vertical green lines overlaid on the spectrum. The amplitude of the fault frequency is calculated by looking for the maximum frequency component in a small window. This search window accommodates small variances in fault frequencies due to slippage and alternate bearings in the same location.
By tracking these condition indicators through time, faults are easily detected and the fault severity is trended through time. Figure 5 shows the time trends of the inner race energy and outer race energy condition indicators on the high speed bearing. Notice that the inner race energy has increased over several months, while the outer race energy has stayed at a constant low value. This divergence in the condition indicator values shows that there is excellent separability of fault location, indicating the system is sensitive enough to not only detect a fault has emerged, but to determine what part of the bearing is affected.

Automated Diagnosis
Calculating and trending condition indicators is important, but without any context they provide little detection capability. To provide an automated diagnosis of a fault, thresholds for each of the condition indicators must be calculated. In Figure 5, the thresholds (warning and alarm) for each of the condition indicators are shown as yellow and red horizontal lines. TurbinePhD uses a patented process to calculate these thresholds and fuse all the condition indicators into one single health indicator. This patented process also eliminates false alarms (indications of a fault when none exists) that require unnecessary trips to the turbine, increasing maintenance costs and causing unneeded downtime.

The health indicator for each component (bearing, shaft, or gear) is scaled between 0 and 1. This allows a user to quickly identify a faulted component without ever having to look at a vibration waveform or frequency spectrum. There are several alert levels based on the component health indicator value:

- **0.0-0.5** – Healthy, no maintenance actions needed
- **0.5-0.75** – Watch, component has an incipient fault but may be too small to visually verify
- **0.75-1.0** – Warning, fault has grown and a visual verification is needed; once the fault is verified, schedule maintenance
- **>1.0** – Alarm, fault is now large enough to produce wear debris that may cause damage on other components; perform maintenance

*Figure 5. The inner race energy and outer race energy condition indicators are trended through time, allowing the tracking of fault severity. In this case, the inner race energy trends upward while the outer race energy stays constant, revealing the separability of the different types of faults.*
Once the health indicator crosses the warning level (HI=0.75), an email is sent to all authorized users; a second email is sent when the health indicator crosses the alarm level (HI=1.0). This notification system allows users to check the health of their turbines only when a fault exists, reducing the monitoring burden and allowing users to focus only on those turbines with problems.

Figure 6 shows the health indicator time series and the alert history for the high speed bearing fault. The health indicator crossed the watch threshold (HI > 0.5) in early April, and then crossed the warning threshold two weeks later on April 19. A borescope inspection was carried out on June 4, almost two months after the initial detection. In the intervening time between the warning and inspection, the health indicator continued to rise, showing that the fault was slowly growing. The inspection revealed a small crack on the inner race of the bearing (see the inset image in Figure 6). At this stage, the crack had created very little wear debris, meaning the probability of secondary damage was still low. This allowed for ample time to plan an up-tower replacement of the bearing.

**BENEFITS**

When a fault is detected early, many components in the gearbox can be replaced up-tower. The difference in the cost of repair is substantial. The actual costs associated with this case cannot be disclosed. However, the table below compares the typical cost of a full gearbox rebuild with an up-tower repair of a high speed bearing. The major cost savings associated with an event like this is driven by two major factors: the elimination of the crane mobilization and the parts and labor savings of replacing one stage of the gearbox instead of rebuilding the entire gearbox. Catching one high speed bearing failure can save well over $200,000. This savings makes the payback time for investing in TurbinePhD very fast, in most cases less than two years.
In the case discussed here, an up-tower repair of the high speed bearing was performed on June 14, 10 days after the borescope inspection revealed damage and more than two months after TurbinePhD alerted the operator to the fault. The turbine was taken out of service, repaired and brought back online in less than 10 hours, minimizing the resulting down time and lost production. Error! Reference source not found. below shows the health indicator value for the bearing immediately after the repair (vertical red line). Note the instantaneous return of the value to normal levels. This case is a great example of the sort of maintenance cost savings that can be gained by deploying the TurbinePhD system on your turbines.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Without TurbinePhD</th>
<th>With TurbinePhD</th>
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<tbody>
<tr>
<td>A bearing in the high speed section of the gearbox develops a crack.</td>
<td>Failure of bearing with secondary damage. Crane needed, full gearbox refurbishment. 14 days of downtime.</td>
<td>Fault detected early, bearing replaced up-tower, no crane needed. 4 days downtime.</td>
</tr>
<tr>
<td>Outcome</td>
<td></td>
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<tr>
<td>Repair Costs</td>
<td>Crane cost: $100,000</td>
<td>Crane cost: $0</td>
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<td></td>
<td>Full gearbox rebuild: $154,000</td>
<td>Up-tower repair: $15,000</td>
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<tr>
<td></td>
<td>Total: $254,000</td>
<td>Total: $15,000</td>
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<tr>
<td>Savings</td>
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<td>Lost Production</td>
<td>14 days downtime* $8,316</td>
<td>1 day downtime* $594</td>
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<tr>
<td>Total Cost</td>
<td>$262,316</td>
<td>$15,594</td>
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<td>$246,722</td>
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*Revenue based on a 1.5MW turbine at 30% capacity factor with $55/MW-hr power price

Figure 7. An up-tower replacement of the high speed bearing on June 14 (vertical red line) took only 10 hours, and the health indicator for the bearing immediate dropped below the alert levels.