The role of oil analysis in wind turbine gearbox reliability

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Barriers to widespread acceptance of wind turbines include their reliability, costs of operation, and maintenance of the equipment relative to alternative means of power generation. The estimated life span of wind turbines is about 20 years and the failure rate is about three times higher than that of conventional generators. Ensuring long-term asset reliability and achieving low operation and maintenance costs are key drivers to the economic and technical viability of wind turbines, and this requires appropriate condition monitoring.

Wind turbines (WT) undergo constantly changing loads, and due to these operational conditions, the mechanical stress placed on the turbines is unmatched in any other form of power generation. Turbines require a high degree of maintenance to provide cost effective and reliable power output throughout their expected life cycle.

The WT gearbox is the most critical component contributing to high failure rates and downtime. Premature gearbox failures are a leading maintenance cost driver as they typically result in component replacement. Oil analysis, along with other condition monitoring tools offers the potential to effectively manage gearbox maintenance by detecting and tracking the severity of early damage.

Routine oil analysis is one of the most widely used predictive/proactive maintenance strategies. It utilises a test slate that evaluates the condition of the in-service lubricant and helps evaluate the condition of internal mechanical components. In short, routine oil analysis is used as a frontline defense against premature gearbox failures.

Three main objectives of oil analysis are to monitor the health of the machine, monitor the health of the oil, and monitor contaminants. Active monitoring provides early warning of abnormal operating conditions that can lead to catastrophic failures if not corrected.

Detecting abnormal wear

The concept behind monitoring wear is uncomplicated: trend the metal wear rates for sudden increases that indicate a change in the system’s health. Wear metal generation rates follow a bathtub curve which represents wear generated over the lifetime of a component, with elevated wear levels during bedding-in, followed by prolonged periods of relatively constant wear levels, followed by the onset of severe wear and an exponential increase in metal generation leading to eventual failure at the end of the component’s life (Fig. 1).

Wear debris generation is a complex phenomenon and wear rates can increase and decrease throughout the lifetime of the gearbox due to factors such as operating loads, lubricant quality, fault progression etc. Even during fault progression, wear rates are highly mutable depending on the microstructural material properties of the wind turbine gearbox components e.g. cylindrical roller bearings.

Commercial oil laboratories employ a variety of techniques to detect (quantify and classify) wear particles in oil, each with its own strengths and limitations. The most widely used and OEM requested techniques will be described below.

Spectrometric analysis

Wear metal particles detected by spectroscopy are typically less than 8 µ in size, and can be generated by rubbing wear or false brinelling (fretting corrosion). Larger particles are generated by more severe wear modes such as fatigue wear, pitting and spalling. Larger ferrous particles present in the used oil sample can be detected by using the PQ method.

The spectrometer is used to determine the presence and concentration of different elements in the oil. These are measured in PPM (parts per million). The measured elements are usually divided into three broad categories: wear metals such as iron, contaminants such as silicon, and oil additives such as phosphorus.

WT gear oil analysis usually requires close monitoring of iron and copper wear rates as these metals are most commonly used in the construction of internal gearbox components. The iron wear rate is usually the highest reading because almost everything in a gearbox is made from different steel alloys. Sources of iron include bearings, shafts, and gears while copper wear usually originates from bronze alloy bearing cages.

Unfortunately the spectrometer can only measure very small particles, usually less than 8 µ in size. The instrument cannot “see” larger particles that might indicate a severe wear situation is developing. 

PQ (particle quantifier) index or ferrous debris monitor

The PQ index or ferrous debris monitor provides...
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a measure of the total ferrous content of the oil sample and from this the total amount of ferrous debris can be determined irrespective of the particles size.

The PQ index is not an actual concentration measurement but it can be compared to the iron (ppm) reading obtained from the spectrometric analysis. If the PQ index is smaller than the iron (ppm) reading, then it is unlikely that particles larger than 8 μ are present. Alternately, if the PQ index increases significantly while the iron reading remains consistent, then larger ferrous particles are being generated and further analysis into the cause of the elevated PQ should be performed.

**Microscopic particle examination (MPE)**

The morphology and quantity of wear particles provide direct insight into overall gearbox health. An MPE is performed by filtering the oil through a membrane of a known micron rating and any debris present is examined under a microscope. The membrane is examined for wear, contamination and colour. An MPE can provide clues to the source of the debris and the potential seriousness of a problem that may be causing it. The individual particles themselves are not categorised but instead observations are recorded for trending purposes using a size and concentration reference matrix.

**Analytical ferrography**

Analytical ferrography involves observing and categorising particle size, shape, colour, and surface texture under magnification. Evaluating the concentration, size, shape, composition, and condition of the particles indicates where and how they were generated. The particle’s composition indicates its source and the particles’ shape reveals how it was generated. Abrasion, adhesion, fatigue, sliding, and rolling contact wear modes each generate a characteristic particle shape and surface condition.

**Particle composition** is broken down into categories that include ferrous wear, white metal, copper, and fibres. Ferrous particles can further be identified as steel, cast iron, dark oxides, or red oxides (rust). A skilled analyst can determine if metallic wear particles are caused by cutting wear, rolling or sliding wear. Wear debris monitoring has been demonstrated to be an effective means of detecting gear and bearing fault initiation.

The main particle types related to the fatigue process encountered in wind turbine gearboxes are laminar micro-particles (micropitting), laminar particles, chunky fatigue particle and spheres. Analytical ferrography can be a powerful diagnostic tool in oil analysis. When implemented correctly it provides a tremendous amount of information about the state of the WT. It is often said that there are three key requirements for maintaining the condition of wind turbine gear oil: keep it cool, keep it clean and keep it dry.

**Detecting oil degradation**

The different modes and severities of oil degradation are dependent upon the oil type, application, and exposure to contaminants. Oil degrades over time due to its ability to react with oxygen in the atmosphere. Oxidation causes the viscosity to increase and acids to form in the oil. The rate at which this occurs can be increased by high operating temperature and the presence of contaminants. In WT gearboxes, oxidation also results in metal corrosion, varnish formation, foaming/air entrainment, poor water demulsibility and filter plugging.

The following tests are usually performed on wind turbine gearbox oils to detect oil degradation/oxidation.

**Kinematic viscosity (KV)**

Kinematic viscosity is defined as a fluid’s resistance to flow under gravity, at a specified temperature, and this in turn determines the thickness of the oil film that prevents contact between metal surfaces. KV is measured in centistokes (cSt) and one centistoke is one mm²/s. Typically, KV is reported at 40°C (KV40) and 100°C (KV100) for WT gearbox oil analysis.

Functions of the lubricant can be categorised into four fundamental groups:

- Reduction of wear
- Removal of contaminants
- Removal of heat
- A structural material

All these functions are negatively impacted if the viscosity of the oil falls outside of the intended viscosity range. If viscosity is not correct for the load, the oil film cannot be adequately established at the friction point. Heat and contamination are not carried away at the proper rates, and the oil cannot adequately protect the component. A lubricant with the improper viscosity will lead to overheating, accelerated wear, and ultimately failure. It is for this reason that viscosity is considered the most important physical property of a lubricant.

Trending of viscosity data is important as deviations from the norm may indicate base oil degradation, additive depletion, or the use of an incorrect lubricant. When the oil’s viscosity increases, it is usually due to oxidation or degradation, typically as a result of extended oil drain intervals, high operating temperatures, the presence of water, the presence of other oxidation catalysts or the addition of an incorrect lubricant.

Decreases in oil viscosity are due to degradation of the viscosity index improver (VII) additive as a result of shear or due the use of an incorrect lubricant during refilling and topping-up. A low viscosity (< 15% of new KV) is generally considered to be more problematic, as this results in a reduced film thickness and the consequent propagation of fatigue cracks associated with micropitting. Micropitting is a surface fatigue phenomenon resulting in superficial damage that appears in high rolling contacts, and is characterised by the presence of small pits on the tooth surface. They first appear in the rolling zone of the gears and then progress towards the root (dentendum) of the gear.

Micropitting causes tooth profile wear, which increases vibration and noise, concentrates loads on smaller tooth areas increasing stress on gear teeth and shortening gear life.

**Viscosity index (VI)**

The viscosity index characterises the effect of temperature on an oil’s viscosity and is of particular importance where operating temperatures vary significantly. The VI can change when the lubricant degrades or degradation byproducts accumulate. The KV at 40°C and 100°C are used to calculate the viscosity index.

**Fourier transform infrared analysis (FTIR)**

Another technique used to detect base oil oxidation is Fourier transform infrared (FTIR) analysis. FTIR analysis measures the concentration of various organic or metallic-organic material present in the oil. When oil is oxidised, the hydrocarbon oil molecules can become restructured into soluble and insoluble byproducts. FTIR measures the accumulation of these byproducts.

FTIR produces an infrared (IR) spectrum (Fig. 2) that is often referred to as the “fingerprint” of the oil as it contains specific features of the chemical composition of the oil. The IR spectrum can be used to identify types of additives, trend oxidation and nitration byproducts that could form as a result of high operating temperatures and thermal degradation caused by aeration/norning.
**Technology**

The technology of impending oil which allows the event to be managed with a significant forewarning concentration. RULER monitoring provides top-treat the oil to replenish the anti-oxidant staff can perform a partial drain and fill or working in a proactive manner, maintenance is a proactive technique used for measuring anti-oxidant additives reserves. The RULER test to resist further oxidation by measuring the base oil after it has occurred. A preferable measurement all reveal damage to the lagging indicator of oxidation. These A change in viscosity and TAN is usually compromised.

**Total acid number (TAN)**

The total acid number is a quantitative measure of acidic compounds in the oil generated as a result of oxidation and the formation of acidic degradation byproducts. The TAN is also utilized as to determine optimal drain intervals. An increased TAN could be the result of increased oxidation. If oxidation is a consequence of oil ageing, the TAN could be used as an indicator of oil serviceability, as high TAN levels could indicate anti-oxidant additive depletion. The TAN of new oil will vary based on the base oil and additive package. As the TAN value of the oil increases, viscosity rises and the lubricating potential of the oil is compromised.

**Remaining useful life (RULER)**

A change in viscosity and TAN is usually a lagging indicator of oxidation. These measurements all reveal damage to the base oil after it has occurred. A preferable scenario would be to evaluate the oil’s ability to resist further oxidation by measuring the anti-oxidant additives reserves. The RULER test is a proactive technique used for measuring anti-oxidant depletion rates and calculating the remaining useful life of the oil.

Working in a proactive manner, maintenance staff can perform a partial drain and fill or top-treat the oil to replenish the anti-oxidant concentration. RULER monitoring provides management with a significant forewarning of impending oil which allows the event to be handled in such a way that cost and impact are minimized.

**Contamination detection**

The third major function of oil analysis is to monitor levels of contamination. Contaminants can be classified as either internal or external. Internal contaminants are generated within the mechanical system such as wear debris from gears and bearings. External contaminants are substances that exist in the environment that should not be in the oil. The most common ones are dirt and water. Contaminants can directly damage the machinery being lubricated. Dirt is abrasive and can cause components to wear abnormally and water causes metals to rust. Contaminants can also cause the oil to degrade which may have an adverse effect on a mechanical system.

Wind turbine manufacturers have increasingly focused on oil quality and cleanliness, which has a huge impact on the lifetime of bearings and the performance of the gearbox. Higher output means more strain on gears, increased mechanical wear and a greater chance of oil contamination. The three main sources of oil contamination in WT gearboxes are moisture, solid particles and air (foam and entrained air). Contamination can enter gearboxes during manufacturing, be internally generated, ingested through breathers and seals, and accidentally added during maintenance.

Air contamination

Air can exist in oil in four different states: dissolved, entrained, foam and free. Dissolved air exists as individual molecules, which are invisible and impractical to detect. Entrained air in oil is comprised of tiny air bubbles suspended in the oil. This air contamination is considered to be the most destructive and can usually be identified by the oil having a cloudy appearance. Foam is a collection of relatively large air bubbles that accumulate on or near the surface of the oil. In the free phase, there are air pockets trapped in dead zones within the mechanical system.

Foam and entrained are the states of air contamination experienced most in wind turbine gearboxes. Foaming and entrained air can damage lubricating oil by increasing the rate of oxidation and thermal degradation, depleting additives, reducing its heat transfer capabilities and reducing its film strength. Entrained air results in increased exposure to oxygen which causes an increase in oil oxidation.

Foam is also an efficient thermal insulator, so the temperature of the oil can become difficult to control. When oil runs hot, viscosity decreases which degrades film strength in frictional zones leading to wear. Foaming is a serious concern in WT gearboxes and is generally the result of a mechanical problem or a chemical issue relating to the condition of the oil. Performing a foaming tendency and air release test can help differentiate between the two causes of foaming as described in Table 1.

**Water contamination**

Different oils have different water contamination handling abilities depending on the base stock and additives used during formulation. The amount of water an oil can carry in solution is known as the saturation point. Once this point is reached, any additional water added will form an emulsion or fall out of suspension as free water. Below saturation level, the water molecules are dispersed alongside the oil molecules resulting in water that is not visible in the oil. This is known as dissolved water, the
least dangerous water state to a lubricated system. When the amount of dissolved water exceeds the saturation point, emulsified water results, characterised by a hazy or cloudy appearance of the oil. Further increases in water content in the oil will result in separate levels of oil and water forming. This state is known as free water.

Water entrainment in gearboxes can significantly degrade the gearbox lubricant by causing it to foam or lose its ability to create sufficient film thickness for elastohydrodynamic (EHL) contact. Water contamination can also cause the formation of rust on internal components, or react with the additives in the lubricant and diminish their effectiveness. There is also the issue of accelerated wear of gearbox components by hydrogen embrittlement (Fig. 3), which is the process by which various metals, including high-strength steel, become brittle and fracture following exposure to hydrogen which is part of the water molecule.

Several different techniques are used by oil analysis laboratories to determine the moisture content of lubricating oil, but Karl Fisher titration is the method preferred by WT turbine gearbox manufacturers and lubricant suppliers, as even small amounts (< 100 ppm) of water contamination can be detected using this method.

Through research performed by a reputable bearing manufacturer, it was found that just 1000 ppm of water contamination could reduce ball bearing life by 70%. Best practice suggests maintaining water levels at or below half of the saturation level of oil at its operating temperature. Thus, if the saturation level is 1000 ppm at 50°C, the caution level should be set at 500 ppm, with the critical level at 1000 ppm.

**Oil cleanliness**

Particle counting involves measuring the cleanliness of the oil and can also be used to evaluate the effectiveness of lubricant filters. Particulate contamination is very damaging to WT gearboxes. It is for this reason that manufacturers have increasingly focused on oil cleanliness as this is critical to establishing equipment reliability, especially as there is a direct correlation between oil cleanliness and component life.

In this technique the number of particles per ml of oil are counted in a variety of size ranges starting at 4 µ and going up to 100 µ. The total number of particles greater than 4, 6 and 14 µ are evaluated and assigned range numbers that indicate the cleanliness of the oil. Particles of approximately the same size as the machine clearances have the greatest destructive potential. Particles the size of or slightly larger than the oil film thickness enter the contact zone and damage surfaces.

While this technique is effective in determining the number and size of particles being generated, particle counting will not identify what the particles are. They could be metallic – both ferrous and non-ferrous, silica, silt, filter fibres, bacteria colonies, varnish agglomerations, water, etc.

With rigorous particle contamination control, bearing life can increase substantially resulting in greater gearbox reliability, uptime and energy production, extended warranty periods and a higher return on investment.

Oil analysis provides a solid foundation on which to build an effective condition monitoring programme in many applications. In the case of WT turbine gearboxes oil analysis has the potential to facilitate the maintenance of wind turbine gearboxes and ultimately, support the more widespread acceptance of this promising form of power generation.

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**Fig. 3: Hydrogen embrittlement mechanism (Noria Corporation).**