POWER Engineering

Contamination Control for Wind Turbine Gearboxes

By William M. Needelman, Marty A. Barris and Gregory L. LaVallee, Donaldson Co. Inc.

Wide variations in speed and load, changing wind direction, climatic extremes and limited space inside nacelles conspire to reduce wind turbine availability and increase maintenance costs. The primary culprit is the gearbox, followed by blades and generators.

Recent estimates show wind farm energy output averages 10 percent below projections and that half the shortfall is due to gearbox unavailability. Operation and maintenance (O&M) costs start escalating in the fourth year of operation, with gearboxes being the single largest issue. While wind turbines have design lives of 20 to 30 years, gearbox warranties are often as short as two years.

The most problematic of all gearbox issues is bearing failures, a challenge expected to increase as turbines get larger. A recent National Renewable Energy Laboratory (NREL) study concluded that the majority of wind turbine gearbox failures start in the bearings.[1]

Gearbox reliability problems are being addressed with advanced designs, better materials and with another important strategy: oil contamination control. Next-generation contamination control technologies, already proven in industrial plants and mobile equipment, can essentially reduce particle and water contamination problems—the two most common and damaging oil contaminants—to zero.

Particle Oil Contamination

Best practices for particle contamination control in wind turbines include the use of inline and offline particle filters and breathers on vents. With rigorous particle contamination control, bearing life can increase 2.6 to 3.7 times, resulting in greater gearbox reliability, uptime and energy production, extended warranty periods and a higher return on investment.

Surprisingly, particles invisible to the unaided eye—about 1 µm in size—can knock out a 20-ton gearbox. How can this happen? In spite of their size, the dynamic clearances between moving parts in gearboxes are also on the order of 1 µm, separated by a thin film of lubricant.

Particles the size of or slightly larger than the oil film thickness enter the contact zone and damage surfaces. In sliding contacts like gear teeth, hard particles plow through and abrasively wear away surfaces while increasing frictional energy losses and heating. In rolling contacts, particles dent surfaces, leading to roughening and surface-initiated fatigue spalling. Hard ductile steel particles, typical of gear wear debris, are the most damaging, but large quantities of any hard particle seriously degrade bearing life.

Particle contamination also reduces the service life of gear lubricants. The surfaces of fresh metallic wear particles and freshly worn components are catalytic, accelerating oil degradation by oxidation. Oxidation products include acids, oil thickeners that lead to cold start problems and gummy substances that coat and insulate heat exchange surfaces and foul flow controls and passages. One classic study found fresh metal surfaces accelerate oil oxidation by six to eight times, as measured by build-up of oil acidity. While copper (found in tubing and bronze bushings) is troublesome, it's likely that the large amount of steel wear debris in gearboxes is the major offender in wind turbines.

Hard ductile particles, typical of gear tooth wear, produce the greatest bearing life decrement. More fragile particles tend to shatter in contact zones, producing less damage per particle. (See Fig. 1.)

Cool, Clean and Dry

There are three key requirements for maintaining the condition of turbine gear oil: keep it cool, keep it clean and keep it dry.

FIGURE 1 PARTICLE CONTAMINATION PROBLEMS IN WIND TURBINE GEARBOXES

Problem	Summary
Surface-initiated Fatigue Spalling	Surface denting followed by crack propagation; leads to pitting/cratering of surfaces
Abrasive Wear	Cutting away material from component surfaces; leads to loss of clearance, high friction
Accelerated Oil Oxidation	Chemically reactive surfaces of fresh metallic wear debris; leads to oil thickening, acidity, fouling gums

Wind turbine gear oil filtration and cooling are often integrated. Coupling the pump and filter takes advantage of a common mount and negates the need for a pump discharge-to-filter inlet pressure line.

To keep gear oil cool, the heat exchanger transfers heat out of the gear oil prior to returning filtered oil back to the gearbox, typically keeping maximum oil operating temperatures below 70 C. To avoid cooling during cold starts, a thermal diverter valve bypasses oil around the heat exchanger until the temperature reaches a minimum of approximately 30 C to 35 C.

To keep gear oil clean, contaminants should be reduced to negligible amounts. Many gearbox manufacturers and bearing experts believe that to eliminate the negative effects of particle contamination oil, cleanliness levels should be maintained at ISO 14/12/10 max, which could bring gearboxes closer to a 20+-year design life. (ISO 14/12/10 is code based on ISO 4406, shorthand notation for particle counts, where the first number is a code for the number of particles greater than 4 µm per mL of fluid, not the actual number; the second number is the count of particles >6 µm; and the last number the count of particles >14 µm.)

Maintaining this cleanliness level, however, requires higher efficiency filtration than has traditionally been used in wind turbines.

Modern gearbox filters are rated bX(C)=1,000. For a filter rated at b5(C) = 1,000, one out of every 1,000 particles equal to or greater than 5 µm passes through the filter while the other 999 particles are captured. Many wind turbine gearboxes now use inline (full-flow) filters rated at 10 µm (b10(C)=1,000). In order to achieve the needed cleanliness level of ISO 14/12/10 max or better, we recommend 5 µm (b5(C)=1,000) inline filters, supplemented with 3 µm (b3(C)=1,000) offline (side-loop) filters if needed.

Achieving this level of cleanliness economically and within the confines of wind turbine nacelles requires novel technologies. Flow restriction across the filter, also known as differential pressure or ΔP, can be especially demanding when filtering high viscosity wind turbine gear oils. This impediment has recently been solved by new filter media based on bi-component fiber technology, such as that developed by Donaldson Co.

Through the judicious selection and design of gear oil filtration and cooling components, maximum protection and longevity can be imparted not only to the gear oil, but the entire gearbox as well.

Water Contamination Problems

In spite of the adage "oil and water don't mix," small amounts of water do dissolve in lubricating oils.

The maximum amount of water that can dissolve in any specific oil, called 100 percent saturation, depends on base stock and additives. For many gear oils, this is in the range of 400-600 ppm.

Small amounts of either free and/or dissolved water contamination (in the parts per million (ppm) range) lead to corrosion and to accelerated abrasive and fatigue wear. Water also reacts with the liquid component of gearboxes, the lubricant. It quickens oil oxidation, generating overly viscous lubes, acids and premature oil replacement.

Contaminant water decomposes ester-base fluids and additives and free water can break emulsions of finely divided anti-wear particle additives, leading to massive additive dumping accompanied by simultaneous fouling of sensors, flow controllers and filters. (See Fig. 2.)

Corrosion, additive drop-out and microbial growth are caused by free water.

Corrosion: Galvanic corrosion requires a current of ions in aqueous solution. Even a thin film of water suffices. Corrosion results in pitting, leakage, weakening and breaking of parts and the release of abrasive particles into the oil such as iron oxide, better known as rust.

Additive drop-out: Certain additives have a strong affinity for water, congregating in and around water droplets. Similarly, water can break colloidal suspensions of finely divided powders sometimes used as anti-wear additives, resulting in dumping of massive amounts of material. Not only are these additives inactivated by water, but additive drop-out can completely foul components, taking them out of action.

FIGURE 2 WATER CONTAMINATION PROBLEMS IN WIND TURBINE GEARBOXES

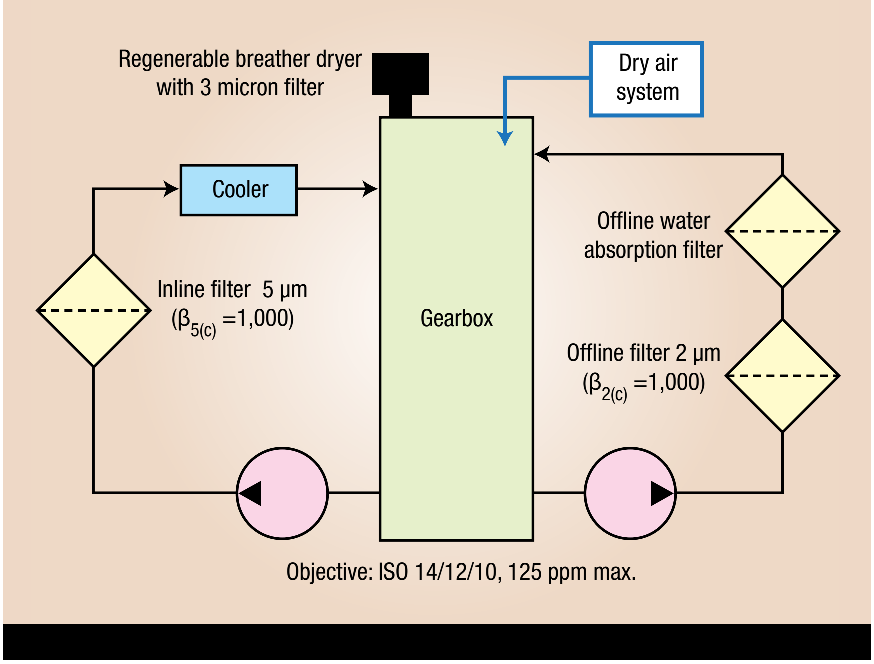
Problem	Summary
Corrosion	Ionic currents in aqueous solution; pitting, leakage, breakage.
Additive Drop-out	Polar hydrophilic additives depletion, also breaking colloidal suspensions of additive particles; loss of additives, parts fouling.
Microbial Growth	Colonization of oils by bacteria and/or fungi; acids, fouling slimes; health issues.
Hydrolysis	Decomposition of ester-based fluids and additives; loss of oil properties, acid and sometimes gel formation.
Accelerated Oil Oxidation	Especially if metal wear debris present, rate of oil oxidation increases by two orders of magnitude; oil thickening, acidity.
Surface-initiated Fatigue Spalling	Water dissociates into O_2 and H_2 at tips of propagating cracks. H_2 migrates into and weakens steel by hydrogen embrittlement; cracks spread faster, reducing life of rolling elements, resulting in surface pits and craters.

Microbial growth: During quiescent intervals and temperatures ranging from 60 F to 125 F (15 C to 52 C), common strains of bacteria and molds multiply and thrive in oil, providing free water is present. Results include accumulation of acids (promoting corrosion since free water is present) and the formation of biological slimes that foul flow passages and moving parts. Microbial growth in oils is also associated with fetid odors, asthma and skin allergies.

Hydrolysis, oil oxidation and surface-initiated fatigue are associated with dissolved water.

Hydrolysis: Ester-based fluids and additives are synthesized by reacting alcohols and acids. Water forms as a by-

Figure 3 MODEL CONTAMINATION CONTROL SYSTEM



product in these esterification reactions. In operating systems, dissolved water can drive the reaction in reverse, decomposing esters back into alcohols (likely innocuous) and acids (quite harmful). Ester-based additives are depleted. The acids promote corrosion, and may also react with metals creating fouling gels.

Oil oxidation: In the classic study mentioned earlier, water was found to accelerate oil oxidation as rapidly as copper. Remarkably, when water was present along with either copper or iron, rates of oil oxidation increased up to 120 times.[2]

Surface-initiated fatigue: During this fatigue process, cracks start at the surface and spread underneath the steel. Gear oil carries dissolved water to the tip of these cracks, where the metal is highly reactive. Water disassociates into its component chemical elements, hydrogen and oxygen gas. The oxygen reacts with either the lubricant or the metal surfaces, but it's the hydrogen that's the major culprit.Hydrogen is the smallest molecule known. Its small size allows it to diffuse through grain boundaries and into the metal, where it weakens the steel by hydrogen embrittlement. This accelerates the propagation of cracks through the bearing steel and shortens the time to spall formation and component failure.

Water Contamination Control

A two-pronged strategy exists for eradicating water contamination problems in wind turbines: minimize water ingression and quickly remove any water that gets in.

The best strategy for curtailing water ingression is to install regenerable breather driers on vents. Older-type desiccant breathers have low water holding capacity and short service life, on the order of weeks to days in humid environments. The new regenerable technology has unlimited service life with respect to water.

Gearboxes "breathe" by thermal cycling. Water is removed during the inhalation phase by thin-film adsorption. During exhalation, the unit regenerates by releasing and returning the previously captured water back to the atmosphere. The device also contains a 3 µm air filter to prevent ingression of airborne particles. Since the particle filter may eventually plug, replacement is recommended every six to 12 months, depending on ambient conditions.

Water may also enter during maintenance activities or through external seals. One method for removing this water is to install a water-absorbing cartridge in an offline position. Preferred units incorporate super-absorbent polymers (SAP) that rapidly remove any free water (95 percent efficiency) and do not pass any water-absorbing substances into the system where they can foul moving parts and flow passages.

Another proven technology derived from other industries has recently been adapted to wind turbines: dry air blankets. Compressed air passes through a pressure swing adsorber producing dry air at -40 C dewpoint. The dry air then sweeps over the surface of gear oil inside a gearbox. Slight pressurization of the system inhibits ingression of humid air. Importantly, the gear oil rapidly dehumidifies by contacting the very dry air. The driving force is transport of water molecules from wet oil (high percent saturation) to dry air (low relative humidity), analogous to air drying a wet towel. In spite of frequent and sometimes massive amounts of water ingression, the dry air blanket system maintained water levels in the 25 percent to 30 percent saturation range, or about 175 ppm for this lubricant.

A Model System

A model contamination control system incorporating best strategies for maintaining clean and dry oil in wind turbine gearboxes is shown in Figure 3. Target particle contamination levels are ISO 14/12/10 or cleaner and water concentrations are 25 percent saturation or drier (typically 100 to 150 ppm).

- Upgrading from the 10 µm and 12 µm filters frequently found in wind turbine gearboxes to 5 µm inline filters is estimated to increase bearing life two and a half or three times. Incorporating both 5 µm inline and 2 µm offline filtration can increase bearing life up to five times.
- Many wind turbine oils are currently operating in the 400 to 500 ppm range. Drying the oil to approximately 125 ppm is estimated to increase bearing life by two to three times.
- Regenerable breather driers on vents inhibit ingression of humid air and offline water-absorbing cartridges containing super-absorbing polymers remove slugs of water. Dry air blankets providing -40 C dewpoint air remove water from gear oil and inhibit humidity ingression.

Implementing these strategies will essentially eradicate particle and water problems. pe

Authors: William M. Needelman is chief science advisor, Marty A. Barris is industrial hydraulics engineering director, and Greg LaVallee is principal engineer, industrial hydraulics, at Donaldson Co. Inc.

References

[1] *"Improving Wind Turbine Gearbox Reliability," W. Musial, S. Butterfield, B. McNiff, NREL/CP-500-41548, European Wind Energy Conference, Milan, Italy, May 2007.*

[2] *"The Effect of Water in Lubricating Oil on Bearing Fatigue Life," Cantley, R.E., ASLE Transactions, 20, 3, 244-248, 1977.*

Donaldson FILTRATION SOLUTIONS

Donaldson Company, Inc.
Industrial Hydraulics
PO Box 1299
Minneapolis, MN
55440-1299 U.S.A.

Tel 800-846-1846 (USA)
Fax 952-703-4652
grphydfilters@donaldson.com
Donaldson.com