New Guidelines For Wind Turbine Gearboxes

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Introduction

The wind turbine industry has been plagued with gearbox failures, which cause repair costs, legal expenses, lost energy production and environmental pollution.

A wind turbine gearbox has failed if it:

- Jams and stops rotating;
- Breaks and allows the rotor to turn without turning the generator;
- Exceeds allowable sound level or vibration limits;
- Has excessive oil leakage;
- Requires excessive maintenance.

Failed gears, shafts, keys, bearings and housings have caused jamming or breaking. Bending fatigue is usually the ultimate failure mode when gearboxes jam or break. However, bending fatigue is often a secondary failure mode initiated by other failure modes such as macropitting or scuffing. Some wind turbines have been destroyed when gearboxes broke and allowed rotors to overspeed.

Strict sound regulations in the United States and Europe require shutdown of noisy turbines because failed gears or bearings cause excessive sound or vibration.

Failed shafts, seals and housings cause excessive oil leakage and, in some cases, loss of lubricant and gearbox failure. Less severe leakage increases maintenance and costs. Soil contamination requires costly cleanup.

Three years ago, a group of individuals dedicated to wind power recognized that many gearbox failures were due to a lack of understanding of the severity of the wind turbine operating environment. They sought to define this environment and improve communication between gear and wind turbine manufacturers so reliable gearboxes could be obtained.

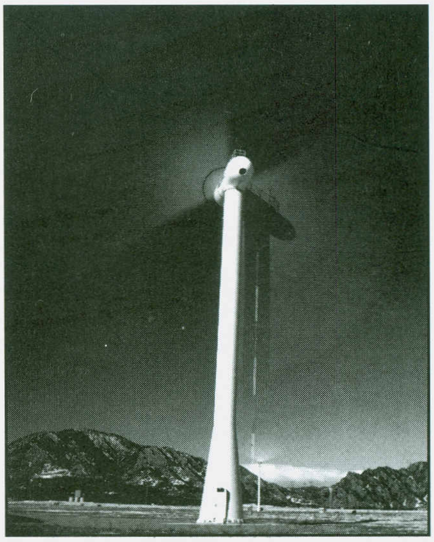
Therefore, the American Gear Manufacturers Association (AGMA) and the American Wind Energy Association (AWEA) formed a committee of wind turbine manufacturers and operators, researchers, consultants and gear and lubricant manufacturers.

The committee developed AGMA/AWEA 921-A97, "Recommended Practices for Design and Specification of Gearboxes for Wind Turbine Generator Systems." The document reflects the latest knowledge about wind loads and failures, plus the insights of gear and wind turbine manufacturers and operators. It describes wind turbine configurations, operating conditions and environmental factors that affect gearbox life. It offers guidelines for defining wind loads and specifying gears, bearings, operation and maintenance. All of these guidelines focus on one goal: ensuring reliable wind turbine gearboxes.

Wind Turbine Configuration and Operation

Two wind turbines with the same generator can experience extremely different gearbox loads. A good control system maximizes energy capture and minimizes structural loads. AGMA/AWEA 921 describes common wind turbines and the significance of their architecture and operation on gearbox loads.

Rotors can be horizontal, as in a HAWT (horizontal-axis wind turbine); or vertical, as in a vertical-axis wind turbine (VAWT). Some HAWTs are integrated systems where the gearbox supports the rotor and, in some cases, the generator and other components such as yaw drives. With this configuration, the gearbox housing must transmit rotor loads to the supporting tower without incurring excessive stresses or deflections. Integrated systems require detailed communication between the wind turbine designer and gear manufacturer to properly design interfaces.



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By contrast, a modular system consists of a rotor, rotor support shaft and bearings, gearbox and generator, each mounted to a common support plate. In this case, the gearbox doesn't need to support external loads.

Rotor torque is controlled by adjusting blade pitch (active control) or by aerodynamic stall (passive control). Active control increases gearbox complexity because, in many cases, the mechanical, electrical or hydraulic control passes through a hollow gearbox shaft to blade actuators. Passive control is simpler, but creates higher peak torques than active control.

Environmental Considerations

Wind turbines must withstand aggressive environments ranging from hot, dusty deserts to cold, wet marine environments.

Temperatures can vary widely, which affects lubrication. The oil sump temperature should be at least 5°C above the lubricant pour point during start-up and less than 95°C during operation. Otherwise, heaters or coolers may be necessary.

All sites require high-capacity, filtered breathers and positive shaft seals to control contamination. Desiccant breathers minimize water contamination. Protective coatings help prevent corrosion.

Defining Gearbox Loads

Many early wind turbine gearboxes failed because designers were uncertain of loads such as:

• Long periods of small oscillation when the brake stops the high-speed shaft, and the wind buffets the rotor;

• Long periods of low speed and light loads during light winds;

• Long periods of high speed and light loads when winds are below cut-in speed;

• High transient loads when the generator connects to the power grid;

• Rapid load fluctuations during normal operation;

• High transient and impact loads during braking.

Defining load spectra for these conditions is difficult due to the uncertainty of predicting loads. However, experience has made predictions more reliable. AGMA/AWEA 921 tells how to assemble load spectra that include both wind loads and transient loads, such as start-up synchronization, rapid blade pitch, actuation of blade control surfaces and braking.

Until recently, wind turbines were not classified according to their capabilities. However, the International Electrotechnical Commission's IEC 1400 initiative has established four classes based on wind severity. A Class 1 wind turbine, for example, can operate in the most severe conditions, with an average wind speed of 10 m/s, an extreme wind speed of 50 m/s and high turbulence intensity.

Specifying Gearbox Components

Experience has shown which gearbox components perform best in wind turbines. The following material summarizes recommendations for gears, bearings and lubrication systems.

Gears. Wind turbine gears are subjected to wind loads that vary from light to very heavy (wind gusts). Carburized, hardened and ground gears have proven reliable under widely varying loads.

Induction-hardened gears were tried, but lacked load capacity because of inadequate accuracy. Carburized and ground gears are the best choice because they have the necessary load capacity and accuracy.

Nitriding is not appropriate for external gears for wind turbines because it has poor resistance to overloads. It has been successful for annulus gears.

Through-hardened gears do not have sufficient load capacity because of their relatively low hardness. In addition, when run with carburized pinions, they promote polishing wear.

Metallurgical quality should meet requirements for Grade 2 material in accordance with ANSI/AGMA 2001-C95.

Gear teeth should be designed to maximize load capacity as explained in AGMA 901-A92. For example,

• Use at least 20 teeth on pinions to achieve good balance between pitting resistance, bending strength and scuffing resistance;

• *Because wind turbine gearboxes are* speed increasers, design profile shift for balanced specific sliding;

• To achieve uniform gear tooth load distribution, use a low aspect ratio (pinion face width to diameter ratio) and modify profiles and helices to compensate for deflections and manufacturing variations;

• To obtain quiet operation, use gears with high contact ratios and high accuracy (AGMA Quality No. 11 or higher).

Preferred gear types for wind turbines are spur, helical and double helical.

Helical gears are quieter than spur gears and have more load capacity. Double helical gears may balance thrust loads; however, they require high accuracy to control dynamic loads, and shaft couplings must be designed and applied to limit external thrust loads.

Spur gears are often used in epicyclic gearboxes because they avoid the tendency of some helical gears to misalign planet gears and interfere with floating sun gears. A combination of spur gears in the low-speed epicyclic stages and helical gears in the high-speed stage provides a compact, quiet gearbox.

As power increases, there are incentives to use epicyclic, split-power-path or hybrid gear arrangements to meet load capacity while limiting size and weight.

Bearings. Severe vibration in wind turbines precludes standard industrial practice for fitting bearing outer races and housing bores. Vibration may cause outer races to spin within their bores, causing wear that misaligns gears, generates wear debris, damages gears and bearings and contaminates lubricant. The worst damage occurs in steel housings because steel-on-steel sliding between outer races and the housing causes scuffing and severe wear. Damage may be less in cast iron housings because dissimilar materials are less likely to scuff. Nevertheless, for reliable wind turbine service, bearing fits must be tight, or races must be mechanically restrained from spinning.

Preferred bearing types for wind turbine gearboxes are spherical roller, tapered roller, double-row, cylindrical roller with retainer, and ball.

Use single-row, tapered roller bearings only if end play is held within acceptable limits under all loads and operating conditions. Otherwise, excessive end play misaligns gears and may cause gear and bearing failures. Measure end play *in situ* so all factors affecting end play, including load deformations and thermal growths, are accounted for.

Full-complement, cylindrical roller bearings offer high load capacity. However, rollers have counterformal contact and opposed sliding that disrupt the lubricant film, allow steel-on-steel contact, create friction and make rollers prone to scuffing. Therefore, use these bearings only on low-speed shafts where sliding speeds are low enough to avoid scuffing.

Wind turbines frequently rotate at full speed under light loads. Under these conditions, bearing loads may be insufficient to maintain rolling contact between rolling elements and raceways. As a result, skidding, overheating and scuffing may cause bearings to fail. The highest risk occurs on high-speed shafts with four-point or angular contact ball bearings. Therefore, specify preload if necessary to prevent skidding.

Wind turbines with high-speed shaft brakes subject a gearbox to reversing loads during a brake stop. Therefore, minimize bearing end play to reduce impact loads on bearings caused by reversing thrust loads from helical gears.

Other tips:

- Equip bearings with bronze retainers. Plastic retainers are susceptible to contamination by hard particles that abrade rolling elements.
- For shaft-mounted gearboxes, minimize radial clearance of low-speed bearings to avoid misaligning the low-speed gear mesh. Modify the helix of the low-speed pinion or gear to compensate for misalignment.
- Except for epicyclic gearboxes, where the sun pinion has no bearings, mount all pinions between bearings. Don't use overhung pinions; they may cause gear misalignment and high bearing loads.

Lubrication

Micropitting, macropitting, adhesion, scuffing, abrasion and other lubrication-related failures are widespread in wind turbine gearboxes. To avoid such failures, the lubrication system should provide an adequate amount of cool, clean and dry lubricant to gears and bearings.

Pressure-fed systems should have a filter to clean the oil and can have a heat exchanger to cool the oil.

Maintenance and condition monitoring should be considered at the design stage.

Many factors need to be considered when selecting a lubricant, including viscosity, viscosity index, pour point, additives, micropitting resistance, scuffing resistance and cost. There are debates on the relative advantages of synthetic vs. mineral oils, especially regarding micropitting resistance. Operators have learned that experiments are required to find acceptable lubricants.

Wind turbine gears have relatively

low pitch line velocity (typically 1–10 m/s) and high loads (contact stress over 1400 MPa). These conditions require synthetic or mineral gear oil with antiscuff additives and the highest practical viscosity (at least ISO VG 320). Too low a viscosity causes micropitting, macropitting, adhesive wear and scuffing.

Micropitting is prevalent in wind turbine gearboxes. Though it does not always lead to catastrophic failure, it generally reduces gear tooth accuracy, increases noise and can progress to full-scale macropitting and gear failure.

To prevent micropitting, maximize specific film thickness by using gears with smooth tooth surfaces and an adequate amount of cool, clean and dry lubricant of the highest viscosity permissible. You may need to experiment with different lubricants to find one with adequate micropitting resistance. FVA Project Number 54 (1) is a standardized test for micropitting resistance of lubricants. A ten-stage pass is minimum acceptable performance.

Running-in gears under controlled loads reduces tooth surface roughness and risks of micropitting and scuffing. However, manufacturers and purchasers disagree on who should perform this task. Gear manufacturers are reluctant to run-in gears because their test facilities are limited; and purchasers are reluctant because they can't always control loads. Therefore, run-in must be negotiated between the gear manufacturer and the purchaser.

Quality Assurance

The purchaser should write a procurement specification for wind turbine gearboxes that fully describes the application, load spectrum and minimum requirements for design, manufacturing, quality assurance, testing and gearbox performance.

The gear manufacturer should prepare plans for quality assurance, inspections and tests.

The purchaser should confirm that the gear manufacturer understands all requirements of the procurement specification before awarding the contract. Criteria for judging gear manufacturer competence are design review meetings, evaluations of manufacturing and QA plans and visits to manufacturing facilities.

To compare competing gearbox designs, AGMA/AWEA 921 recommends these standards for rating the components:

- Gearbox: ANSI/AGMA 6001, ANSI/AGMA 6010 or ANSI/AGMA 6023.
- Gears: ANSI/AGMA 2001.
- Bearings: ANSI/AFBMA 11.
- Shafts and keys: ANSI/AGMA 6001.

Plans should clearly define all acceptance criteria before manufacturing starts. After awarding the contract, the purchaser should audit manufacturing, inspection and testing for conformance to the procurement specification.

Prototype gearboxes should be qualified before full-scale production begins. Prototype gearboxes should not be manufactured until the purchaser approves all elements of first-article inspections and tests. After prototypes have met the requirements of the procurement specification, and manufacturing plans are sound, the transition to production should be straightforward.

Operation and Maintenance

The gear manufacturer, lubricant supplier and purchaser should establish plans for start-up, operation and maintenance before gearboxes are placed in service. Gearboxes should be run-in under controlled loads to reduce the risk of scuffing and micropitting and prolong gear and bearing lives.

Regular gearbox inspections should be done at run-in and at specified intervals. AGMA/AWEA 9021 gives guidelines for on-site monitoring and laboratory analyses of lubricants for viscosity, water content, acid number, solid contaminants and additive depletion. It also describes methods for monitoring vibration and temperature.

Safety is a major concern for wind turbine operators because of the risk of falling, being trapped in rotating components or being injured while maneuvering in restricted spaces. Gearboxes should have an adequate number of steps, handholds and lanyard hook points. Housings should have rounded corners, and all exposed rotating components should have safety guards. Because access is difficult and work space is limited, design the gearbox to ease maintenance. ○

References:

1. FVA-Information Sheet, "Micropitting," No. 54/7, July, 1993. Forschungsvereinigung Antriebstechnik e.V., Lyoner Strasse 18, D-60428, Frankfurt/Main, Germany.

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