IMPROVING WIND TURBINE GEARBOX RELIABILITY

How high-performance wind turbine gear oil cleanliness and filtration can reduce total cost of ownership

TECHNICAL WHITE PAPER

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SETTING **THE SCENE**

The growth in demand for energy and the focus on reducing carbon dioxide emissions is increasing the utilisation of renewable energy sources such as wind power. Data released by the Global Wind Energy Council in its Global Wind Report 2016 show that the total installed wind turbine capacity reached almost 487 GW in 2016. There were 54 GW worth of new installations. All these turbines provide some 3.7% of the world's total electricity supply (Figure 1).

China continues to lead the world with 42.7% of the new installed capacity in 2016 and 34.7% (168.7 GW) of the total global installed capacity. The markets of China, the USA, Germany, India and Spain account for 67% of the world's installed wind power capacity. Chinese wind turbine manufacturers, including Goldwind, Guodian United Power Technology, Envision Energy and Mingyang Wind Power, were in the top-10 leading turbine manufacturers in 2016 and main gearbox manufacturers such as NGC Gears and Chongqing Gearbox have major market shares in the domestic and global markets.[1]

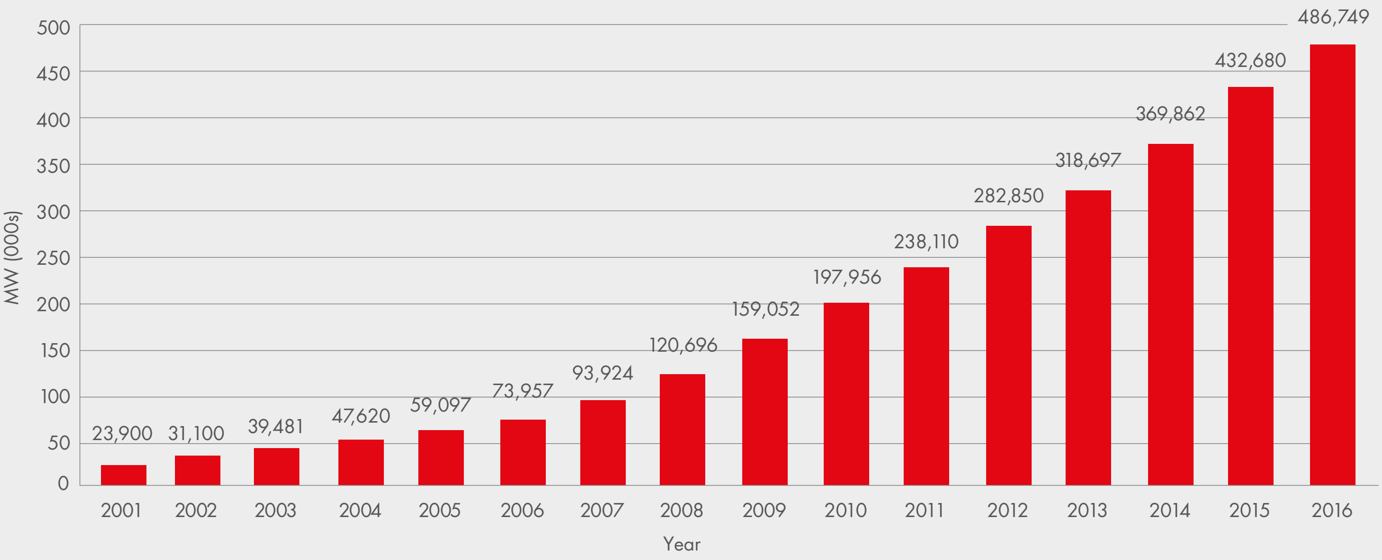


FIGURE 1: Global cumulative wind turbine installed capacity, 2001–2016 (source: Global Wind Energy Council 2017).

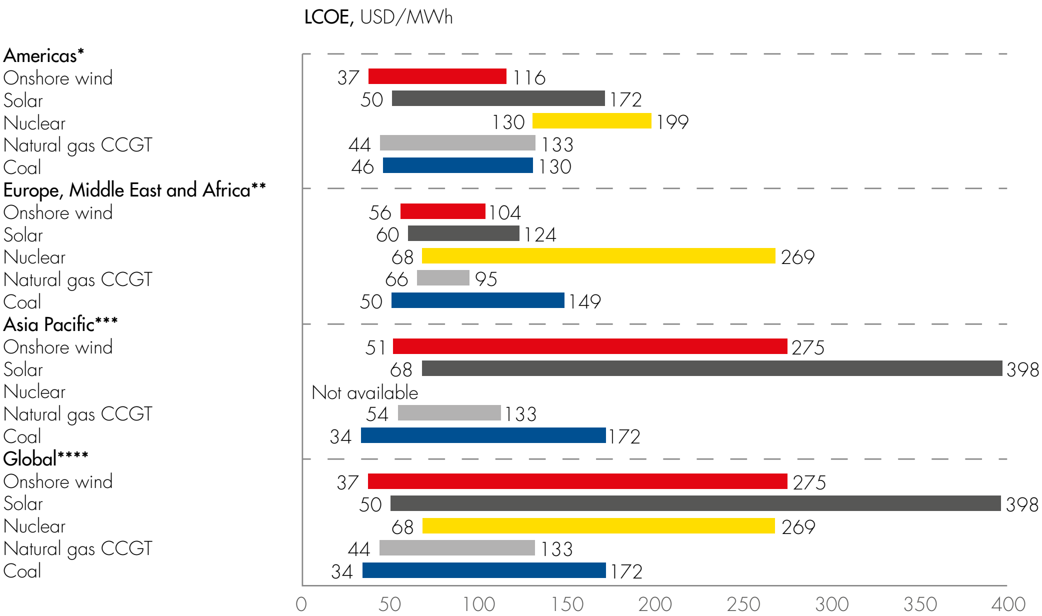
COST-COMPETITIVE WIND POWER GENERATION

Wind turbine manufacturers and wind farm operators continuously strive to reduce the overall costs associated with wind power generation. These costs include operating and maintenance costs as well as the initial capital expense, as wind farm operators are seeking ways to improve turbine reliability, reduce unplanned maintenance and lower their total cost of ownership.

Wind power is rapidly becoming cost-competitive on a cost-per-megawatt-hour basis relative to competing forms of power production (Figure 2). The levellised cost of energy (LCOE) is used as a metric to compare the relative costs of power generation over the lifetime of a power plant. The LCOE is the ratio of the total cost of power generation to the amount of electricity generated. Industry data show that onshore wind power is now competitive in terms of LCOE (Figure 2) with fossil fuel steam, gas and combined cycle power plants, but offshore wind remains more costly on an LCOE basis. At $126/MWh, it is almost twice the cost of onshore wind at $68/MWh.[2]

Significant technology advances will see the LCOE for wind power becoming even more competitive: that for onshore wind is set to decrease by between 23 and 36% by 2030.[2]

Shell Lubricants works with customers in the wind power sector over the entire value chain to help reduce their total cost of ownership and to implement solutions designed to optimise gearbox, bearing, lubricant and grease life. According to an international industry study commissioned by Shell Lubricants, the savings opportunity lubricants offer is recognised but undervalued.[3] The study found that 58% of companies recognise that lubricant selection can help to reduce costs by 5% or more but fewer than 1 in 10 (8%) realise that the impact of lubrication could be up to six times greater than this.



*Source: Bloomberg New Energy Finance: H2 2016 LCOE AMER Outlook. October 2016

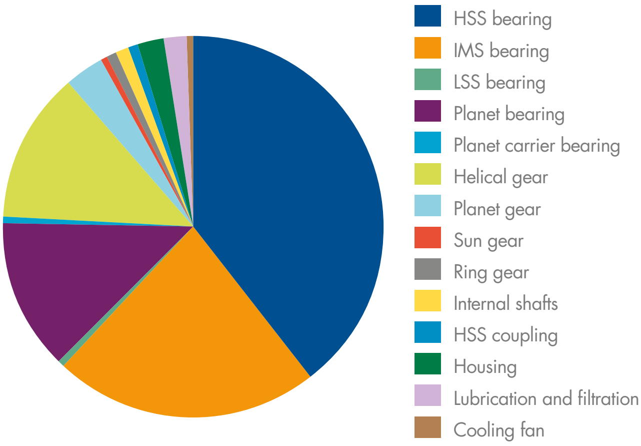
**Source: Bloomberg New Energy Finance: H2 2016 LCOE EMEA Outlook. October 2016

***Source: Bloomberg New Energy Finance: H2 2016 LCOE APAC Outlook. October 2016

****Source: Bloomberg New Energy Finance: H2 2016 Levelised cost of electricity update. October 2016

FIGURE 2: Relative LCOE for different forms of energy.

WIND TURBINE GEARBOX DESIGN LIFE – THEORY AND PRACTICE



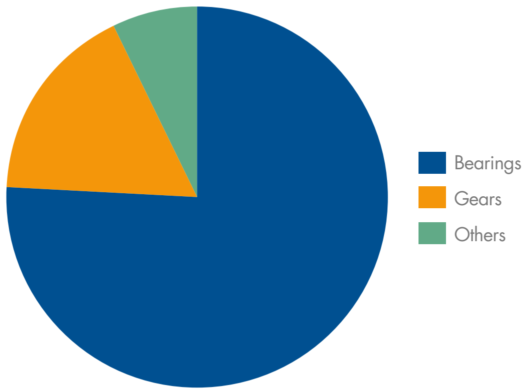


FIGURE 3: Data from National Renewable Energy Laboratory's gearbox reliability collaborative failure database showing wind turbine gearbox failure factors. The charts are based on about 1,050 confirmable records provided by wind farm operators from 2009 through to August 2016.[5]

According to IEC 61400-1, *Wind turbines – Part 1: Design requirements,* the design life of a wind turbine should be at least 20 years for classes I to III (wind speed classification). This applies also to all the components and subcomponents of the turbine. Hence, gearboxes and bearings also have a 20-year design life requirement.

The gearbox in a wind turbine is recognised as being a critical component that may contribute to a high percentage of wind turbine downtime costs. IEC 61400-4, *Wind turbines – Part 4: Design requirements for wind turbine gearboxes*, provides guidelines for designing wind turbine gearboxes to achieve high levels of availability and reliability. Practical field experience has highlighted a gap between the realised and the theoretical wind turbine gearbox reliabilities. Wind turbine insurance company GCube Renewable Energy Insurance has reported that there are about 1,200 incidents of gearbox failure each year among the geared turbines in operation worldwide.[4] The insurance claims related to these failures commonly range between $200,000 and $300,000; in some cases, they have exceeded $500,000.

An ongoing survey by the National Renewable Energy Laboratory into gearbox reliability suggests that, although there may be many contributors to gearbox failure and reduced reliability, bearings account for over 70% of failures in its database (Figure 3).[5] Of those, almost 50% relate to high-speed shaft bearings. Axial cracking (also called white etch cracking) is one commonly indicated failure mode. Figure 3 shows the distribution of component failures, as based on that report. One bearing manufacturer has reported bearing failures occurring frequently within the first 1–3 years of operational time, or at 5–10% of the calculated rating life.

Several studies on wind farms in Europe and North America show that although gearbox failures are not as common as those for components such as electrical systems are, they result in the highest downtime and replacement costs (considering the associated costs for cranes, replacement parts, labour and downtime). With improvements in design, manufacture and operating and maintenance procedures, the downtime associated with onshore wind turbine gearbox failures has fallen over the years, yet downtime and wind turbine reliability remain ongoing concerns for operators.

SOLUTIONS FOR ADDRESSING **WIND TURBINE GEARBOX RELIABILITY**

Taking into consideration the lubricated components in the wind turbine gearbox, including the multiple roller element bearings, how can improved reliability be achieved and the design life (often referred to as the L10 rating life) be reached? There are several ways that bearing reliability can and is being improved through design (for example, through the use of black-oxide coatings), lubrication, contamination control and maintenance practice solutions. Using a combined approach, operators have been able to reduce the incidence of failures.

Detailed bearing life calculations are available in ISO/TS 16281:2008, *Rolling bearings – Methods for calculating the modified reference rating life for universally loaded bearings*. This also cites ISO 281:2007, *Rolling bearings – Dynamic load ratings and rating life*. The full details of the calculations and equation derivations are beyond the scope of this paper. However, these documents provide the basis for the relationship between bearing life and gear oil cleanliness and contamination control.

HIGH-PERFORMANCE WIND TURBINE GEAR OIL

In the early days of wind turbine gearboxes, micropitting of gears was a very common failure mode. However, engineering design, surface finishing and lubrication solutions have been identified to help reduce the incidence of such failures. Wind turbine gear oils such as Shell Omala S4 GX 320 and the new Shell Omala S5 Wind 320 are designed to have excellent resistance to scuffing wear and a high level of micropitting resistance in industry-standard tests. These tests include the FZG and FVA scuffing and micropitting tests run under variable speed and temperature conditions, including low-speed, high-torque conditions. Well-designed synthetic wind turbine gear oil will have pass results for scuffing wear under both single- and double-speed conditions and when tested at 60°C and 90°C with a failure load stage of 14 or more.

As the high incidence of failure in the bearings of wind turbines indicates, ongoing efforts to address bearing failure are required. Shell Lubricants is actively involved in research to develop new wind turbine lubricant technology such as the new Shell Omala S5 Wind 320 wind turbine gear oil; joint studies on the effects of different lubricant additive chemistries on white etch cracking mechanisms; and research into the utilisation of condition monitoring techniques, both on-line sensor technology and offline oil analysis.

Leading bearing manufacturers such as SKF, FAG and Timken have developed test procedures to assess the performance of gear oil under a variety of different lubrication regimes. The FAG step 1 to 4 roller bearing test, for example, evaluates fatigue behaviour under the conditions of boundary lubrication, mixed friction and elastohydrodynamic lubrication, including when contaminated with water. Shell Omala S5 Wind 320 and its predecessor Shell Omala S4 GX 320 give pass results in this severe test and showed low wear to roller bearings and bearing cages throughout the test.

Wind turbines often operate in very wet coastal or offshore environments, where protecting bearings against the corrosive effects of seawater is vital. The gear oil should resist the formation of harmful deposits and retain its protection against bearing wear when contaminated with water. When designing wind turbine gear oil, it is necessary to ensure a combination of base oil and additive system that protects against rust and corrosion, even if the oil becomes contaminated with water. This property is evaluated in tests such as the ASTM D665A rust test, the ASTM D130 copper corrosion test and the SKF EMCOR test, which can be run with both distilled and salt water. Shell Omala S5 Wind 320 exhibits excellent protection in the SKF EMCOR salt-water corrosion test wear where the bearings are rated as new with a 0–0 rating at the end of the test (Figure 4).

SKF EMCOR test (ISO 11007)	Corrosion degree
Distilled water	0–0
Water + 0.5% NaCl (i.e., offshore)	0–0

FIGURE 4: Shell Omala S5 Wind 320 demonstrates excellent resistance to corrosion in the SKF EMCOR test.

CONTAMINATION CONTROL

Bearing life is also influenced by the presence of external contamination such as particulates or water as well as by load, temperature and speed. Particulate contamination in lubricants is a major contributor to premature bearing and gear failure. Maximising bearing life, and hence improving reliability, requires a focus on reducing the amount of particulates in the oil that can lead to abrasive wear. Particulates may be introduced either externally through inadequate seals and breathers or poor lubricant storage and handling, or internally as wear by-products. To reduce the level of external contaminants, using filtration during gearbox filling and in service is vital.

Wind turbine gear oil must be filtered before its addition to gearboxes and in service to specific values set by industry standards and equipment manufacturers. The IEC 61400-4 standard sets the requirements shown in Table 1 for wind turbine gear oil cleanliness. Many gearbox and wind turbine manufacturers and international standards have now adopted such levels as part of their gear oil supply requirements.

Shell Omala S5 Wind 320 is manufactured in state-of-the-art blending facilities and is certified to have an ISO 4406 cleanliness rating of –/14/11 or better.

Wind turbine gearboxes contain one or more mechanical in-line filtration systems (Figure 5(a)), which are often combined with the cooling circuit. The exact location and number of filters, type (beta ratio and micron rating) and media will vary by manufacturer. The most common in-line filter the wind industry uses is a two-stage 50-μm/10-μm element with an inbuilt bypass valve supplied by filter manufacturers such as HYDAC, Pall, Internormen and Mintai Hydraulics Shanghai. The filter medium is commonly a synthetic fibreglass medium.

Sample origin	Cleanliness required as per ISO 4406:99
New oil added to gearbox at any location	–/14/11
Bulk oil from gearbox after factory test by the gearbox manufacturing facility	–/15/12
Bulk oil from gearbox after being in service for a month after wind turbine commissioning	–/15/12
Bulk oil from gearbox sampled as per maintenance schedule	–/16/13

TABLE 1: The requirements for wind turbine gear oil cleanliness (Source: IEC61400-4).

Increasingly, wind turbine manufacturers and wind farm operators are retrofitting offline filters (Figure 5(b)) to improve the cleanliness of gear oil and thereby extend bearing life. Such offline filters most commonly use depth filtration via cellulose media with a 5- or even 3-μm absolute rating. Major suppliers include CC Jensen, HYDAC and Mintai Hydraulics Shanghai.

The oil flow rate through inline filters can be very high, up to 200 l/min, while that in an offline filter is much slower at 45–60 l/h. With such high flow rates and minimal residence time in the gearbox, it is important that gear oil has very good low foaming tendency and rapid air release. Consequently, it is important that the wind turbine gear oil be tested for suitability for use with different filter media, especially offline media.

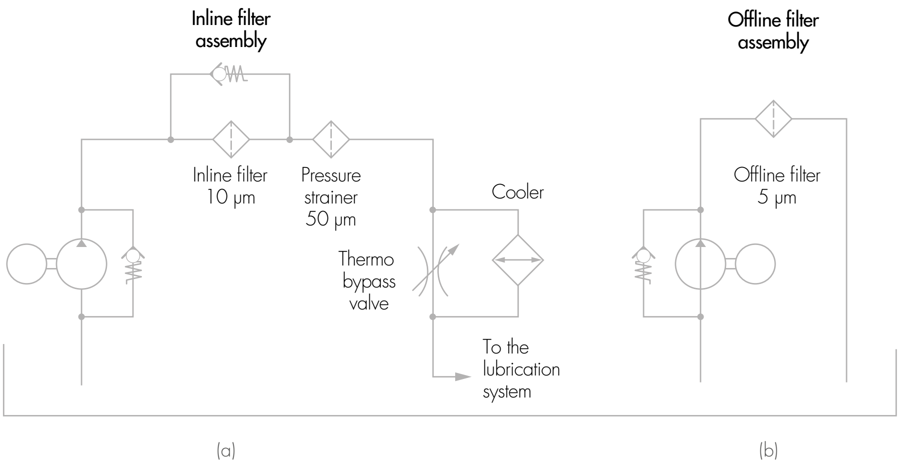


FIGURE 5: (a) Typical location of inline filtration and (b) offline filtration (Source: IEC 61400-4).

Shell Omala S5 Wind 320 has been rigorously tested with leading filter manufacturers, including HYDAC, Pall, CC Jensen, Mintai Hydraulics Shanghai, Sichuan CRUN and Triple R America, to ensure it retains its foaming performance even with fine offline filtration. After extended cycles through a 3-μm fine filter, some gear oils exhibit an increase in foaming tendency. **Shell Omala S5 Wind 320, however, retains excellent antifoaming performance, even under extended testing with commonly used offline filter media** (Figure 6).

BEARING COATINGS

In response to premature bearing failures in the field, several bearing manufacturers have introduced black-oxide-coated bearings for use in wind turbine gearboxes. Black oxide is a surface treatment formed by a chemical reaction on the surface layer of the steel bearing. Black-oxide coatings have been shown to reduce the rate of bearing failures in the field when compared with failure rates for non-coated bearings and the risks of premature bearing failure associated with fretting wear, micropitting and axial cracking through the improved resistance to corrosion they provide.

LUBRICATION PRACTICES AND CONDITION MONITORING

As with any lubricant, appropriate storage and handling procedures should be used for wind turbine gearbox oil to maintain product performance. Giving attention to gearbox breathers and filters in service is important for protecting against particulate and water ingress.

Analysing the oil in a wind turbine's main gearbox should be a key component in a reliability and condition-based maintenance programme.

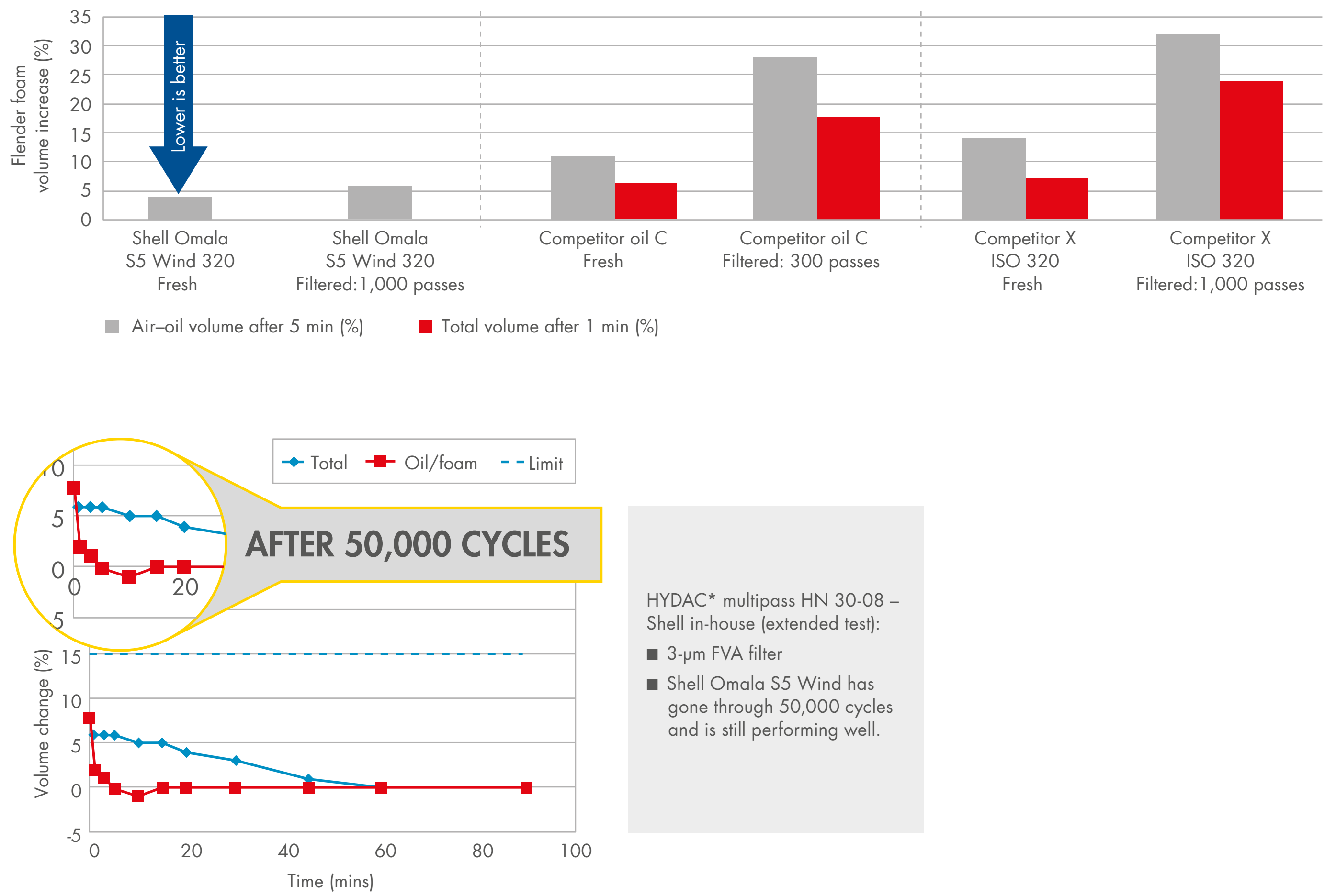


FIGURE 6: Shell Omala S5 Wind 320 retains excellent antifoaming performance even after many filtration passes.

Consequently, Shell Lubricants offers the Shell LubeAnalyst oil condition monitoring programme to wind farm operators.

Regular sampling and testing, typically six-monthly (more often in the event of operational issues), can provide key insights into gear oil contamination and degradation, and gearbox condition. Testing of main gearbox oil and hydraulic fluid helps operators to understand the condition of their turbines' gearboxes and oil. Trending software is available to benchmark the performance of a given unit across an asset portfolio. Critical oil parameters such as viscosity, water content, particulate contamination, wear metals and degree of oxidation are typically evaluated. More extensive testing, including ferrographic analysis and foaming tendency, is also available. Shell experts can help customers to understand the benefits of the oil analysis programme and to learn how to use the software and how to read oil analysis reports.

Changing the gear oil in a wind turbine, whether because of end of service life, excessive contamination, deposit formation, trips or gearbox damage, presents logistical challenges. The remoteness of wind farms, the often-harsh climatic conditions (low and high ambient temperatures) and the height of the towers to be climbed all mean that a successful gearbox oil changeover needs careful planning. **Shell Lubricants' technical staff have developed wind turbine gear oil flushing procedures that can be used to facilitate oil changeover and that have been applied successfully to many in-service wind turbines.** This experience has shown the process provides a lower carryover of the residual in-service oil to the new gear oil fill. The process can help with extending the oil-drain interval of the new oil, reduce the frequency of oil filter changes and prevent unplanned outages and trips.

SUMMARY

As operators look to improve their wind turbine reliability and extend the lives of gearboxes and bearings, the use of high-performance lubricants and greases and associated service solutions to help reduce total cost of ownership is vital. Shell Omala S5 Wind has been developed to address the common challenges equipment manufacturers and operators face. The first production of Shell Omala S5 Wind in China took place in April 2017 in Tianjin, thereby bringing our latest product development to the Chinese market.

As new gearbox designs are developed and awareness of failure mechanisms and root causes increases, Shell continues to innovate by bringing new technology to the market and working closely with component and wind turbine manufacturers and operators to improve wind turbine reliability.

REFERENCES

[1]Bloomberg New Energy Finance: about.bnef.com/blog/vestas-reclaims-top-spot-annual-ranking-wind-turbine-makers

[2]2016 H2 data, Bloomberg New Energy Finance: about.bnef.com/blog/h2-2016-lcoe-giant-fall-generating-costs-offshore-wind

[3]Survey commissioned by Shell Lubricants and conducted by Edelman Intelligence, based on 121 interviews with power sector staff who purchase, influence the purchase or use lubricants/greases as part of their job across 8 countries (Brazil, Canada, China, Germany, India, Russia, the UK and the USA) from November to December 2015

[4]GCube: Grinding gearboxes: Global trends in wind turbine downtime grinding gears (2014) www.gcube-insurance.com/en/press/gcube-gets-to-grips-with-grinding-gearboxes

[5]www.nrel.gov/wind/grc-research.html

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