CONTINUOUS, ONLINE DETECTION OF CRITICAL OPERATING CONDITIONS AND WEAR DAMAGE WITH A NEW OIL CONDITION MONITORING SYSTEM, WEARSENS®

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Abstract: An online web-based oil diagnosis system for the early identification of critical operating conditions for premature failures of rolling bearings in industrial and particularly wind energy gearboxes by white etching cracks is presented. The new approach utilizes sensor detection of chemical aging of the lubricant and its additives due to critical operation conditions. The presented sensor system effectively controls the proper operation conditions of bearings and cogwheels in gears. The online diagnostics system measures components of the specific complex impedance of oils. For instance, metal abrasion due to wear debris, broken oil molecules, forming acids or oil soaps, result in an increase of the electrical conductivity, which directly correlates with the degree of contamination of the oil. For additivated lubricants, the stage of degradation of the additives can also be derived from changes in the dielectric constant. The determination of impurities or reduction in the quality of the oil and the quasi continuous evaluation of wear and chemical aging follow the holistic approach of a real-time monitoring of an alteration in the condition of the oil-machine system. Once the oil condition monitoring sensors are installed on the wind turbine, industrial gearbox and test stands, the measuring data can be displayed and evaluated elsewhere. The signals are transmitted to a web-based condition monitoring system via LAN, WLAN or serial interfaces of the sensor unit. Monitoring of the damage mechanisms during proper operation below the tolerance limits of the components enables specific preventive maintenance independent of rigid inspection intervals.

Keywords: chemical oil aging, oil additive degradation, online oil condition monitoring, industrial gearboxes, critical vibration loading, early bearing failures, white etching cracks, hydraulic systems.

1. PRINCIPLES OF OPERATION

With the WearSens® unit, components of the complex impedances X of oils, in particular the specific electrical conductivity κ and the relative permittivity ε_r as well as the oil temperature T are measured [1-3]. The values κ and ε_r are determined independently of each other. Figure 1 shows the sensor with its triple plate design.

Oils are electrical non-conductors. The electrical residual conductivity of pure oils lies in the range below 1 pS/m. Figure 2 illustrates conductivities of various materials.

The conductivity range of the presented sensor system is marked in green. It starts below the conductivity of the distilled water. For comparison, the electrical conductivity of the electrical non-conductor distilled water is larger by six orders of magnitude.

Figure 1. Sensor with triple plate design
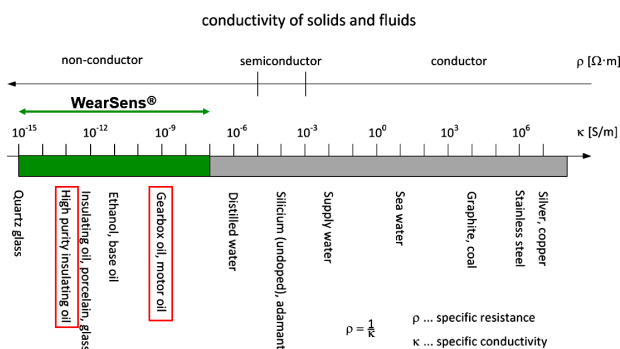
Figure 2. Conductivities of liquids and solids, measurement range of the presented sensor system is marked in green

Abrasive (metallic) wear, ions, broken oil molecules, acids, oil soaps, etc., cause an increase of the oil conductivity κ. It rises with increasing ion concentration and mobility. The electrical conductivity of almost all impurities is high compared with the extremely low corresponding property of original pure oils. A direct connection between the electrical conductivity and the degree of contamination of oils is found. An increase of the electrical conductivity of the oil in operation can thus be interpreted as increasing wear or contamination of the lubricant. The aging of the oil is also evident in the degradation of additives. The used additives reveal high conductivity compared with the oil.

In Figure 3 the data acquisition and data processing in the sensor system is sketched with the field data acquisition, data processing and signal output.
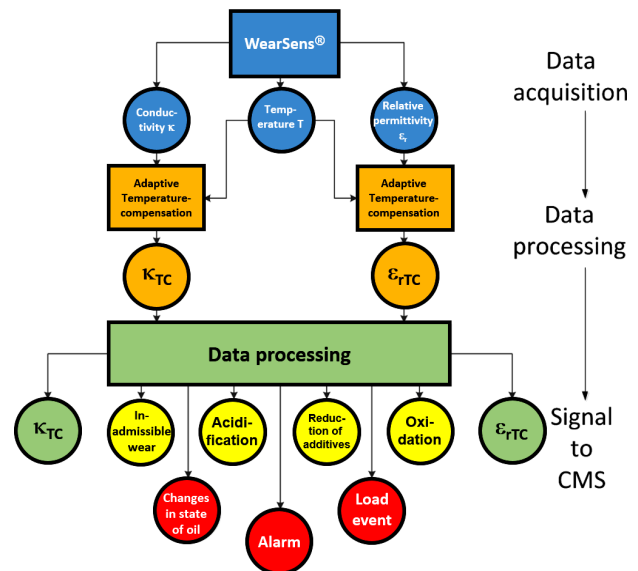

Figure 3. Data flow graph of the sensor system

The rectangular boxes represent autonomous functional units with defined responsibilities. They are characterized by inputs and feedback-free outputs. The individual instances communicate with each other via the data spaces shown as circles. Data flow is characterized by means of arrows between data spaces and instances. The instance network allows a static interpretation of the catchment area of the individual functional units.

2. TEMPERATURE COMPENSATION AND MEASUREMENT ACCURACY

Ion mobility and thus, electrical conductivity κ are dependent on the internal friction of the oil and therefore, also on its temperature. The conductivity κ of the oil increases with temperature. The type of contamination and its temperature dependence cannot be assumed to be known. To improve the comparability of measurements, a self-learning adaptive temperature compensation algorithm is necessary. A change of the oil quality can then be assessed by the temperature compensated conductivity value, even though the specific contamination is not determinable. The relative permittivity is measured with the same basic sensor arrangement as used for the determination of the electrical conductivity.

Figure 4 shows the effect of temperature compensation.
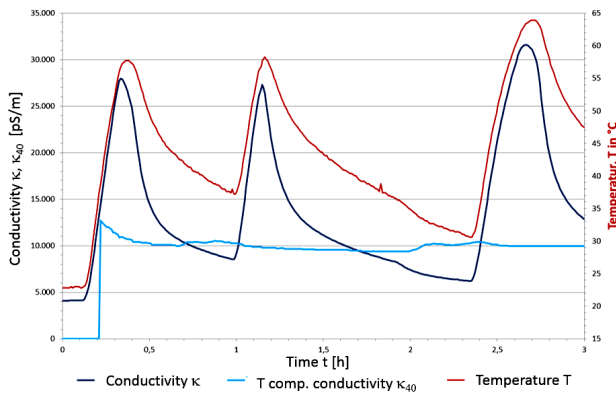
Figure 4. Temperature compensation algorithm

While the conductivity κ changes significantly with temperature, the temperature compensated conductivity κ_{40} stays nearly constant.

## 3. APPROACH FOR CONDITION MONITORING OF ADDITIVATED LUBRICATING OILS

The consumption of the additives is reflected in a reduction of the electrical conductivity and permittivity of the oil. The gradient, i.e. the time derivative, of the conductivity or the dielectric constant progression respectively represents a measure of the additive degradation and consumption. The full additive degradation is indicated by the slope of zero (bathtub curve). Then the measurement signal increases further with increasing pollution, water entry, etc.

Figure 5 schematically shows the temperature compensated time curve of the permittivity of additivated oil continuously contaminated by the addition of wear debris, water or oil acids from chemical aging:

Region A: Polar additives are combining with impurities, particles, acid and soap products, which reduces the additive content in the lubrication oil and result in a decrease of the relative permittivity ε_{r40}.

Point B: Full additive degradation.

Region C: Due to the lack of additive components new generated polar elements can't be chemically neutralized anymore, which leads to an increase of the relative permittivity ε_{r40}.
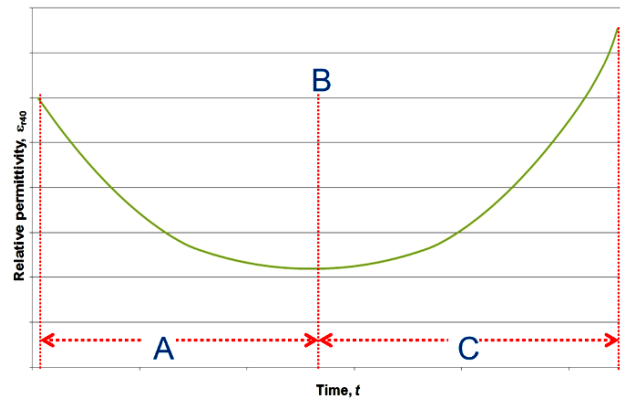

Figure 5. Model of the temperature compensated permittivity

## 4. APPLICATION: HYDRAULIC ACTUATOR

This section demonstrates the oil sensor application for the condition monitoring of a hydraulic actuator used for wind turbine testing. The basic setup of this blade fatigue test is depicted in Figure 6.

During the **G**round **R**esonance **Ex**itation (**GREX**) the hydraulic actuator applies automated cyclic loading to the blades at its resonant frequency [4].
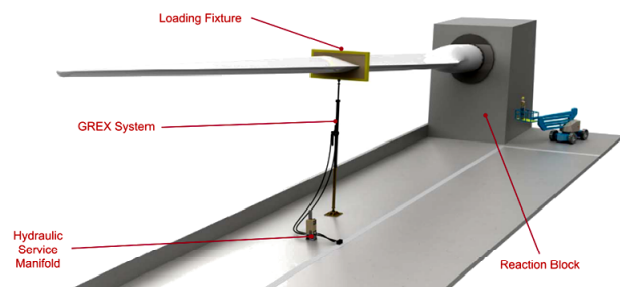

Figure 6. Rotor blade test stand with GREX [4]

The schematic of the hydraulic oil flow is shown in Figure 7. The hydraulic oil tank
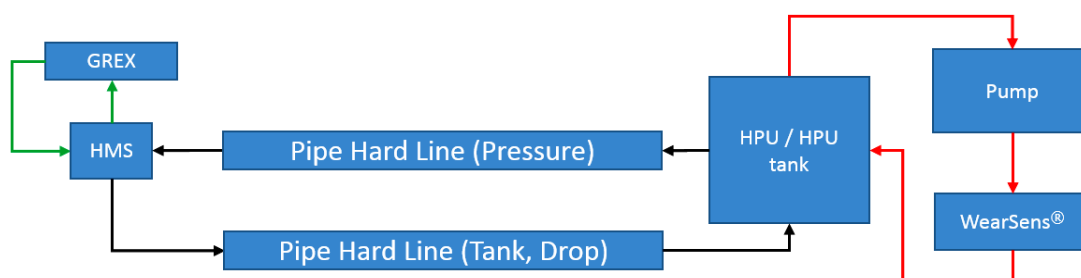
**Figure 7.** Scheme of the hydraulic oil cycles at the GREX installation

contains about 1900 Litre; a flow rate of 600 Litre/minute is set between the tank and the hydraulic service manifold (HMS). The HMS regulates the cyclic hydraulic pressure on the actuator, to excite the rotor blade at the resonance frequency. A lower flow rate, 100 ml/minute, is used in the oil cycle with the WearSens sensor. By these flow settings it is assured that there is sufficient oil exchange in each oil cycle via the HPU tank.

The presented data in Figures 8 and 9 was recorded during a long term rotor blade fatigue test run; the oil sensor system was installed to continuously monitor the hydraulic oil quality, for preventing the actuator from damage.
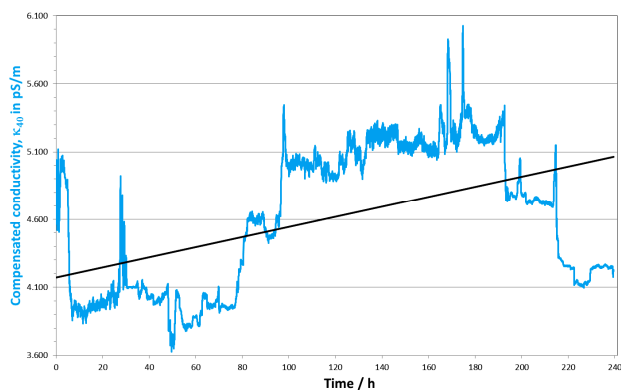
Figure 8. Temperature compensated conductivity over time

The data in Figure 8 shows the temperature compensated electrical conductivity κ_{40} over time: a continuous increase during normal operation of the hydraulic actuator system has a smaller gradient than critical operation conditions, which are visible in sharp peaks.
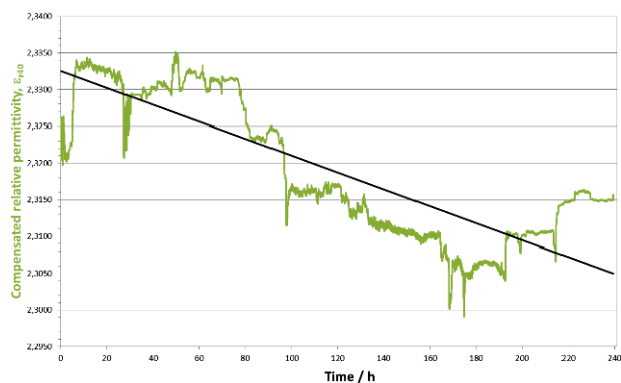
Figure 9. Temperature compensated relative permittivity over time

The decreasing trend line signals the continuous consumption of polar additives in the hydraulic oil due to the actual load over the complete measurement run. Limit settings in the relative permittivity ε_{r40} and the corresponding gradient of ε_{r40} can be used to perform maintenance on demand for adding new additives packages to enable a stable hydraulic oil quality.

# 5. WEB-BASED DECENTRALIZED LUBRICANT QUALITY MONITORING SYSTEM

The integration into a suitable communication structure and the realization of an online monitoring system offers an interesting practice-oriented utilization of the oil sensor system. This is briefly discussed below.

Preferred areas of application of the sensor system are energy production and automated technical plants that are operated locally, like e.g. wind turbines, generators, hydraulic systems or gearboxes. Plant employers are interested in continuous automated in vivo examination of the oil quality rather than interrupting the operation for regular sampling. Online oil status monitoring significantly improves the economic and ecological efficiency by increasing operating safety, reducing down times or adjusting oil change intervals to actual requirements. Once the oil condition monitoring sensors are installed on the plants, the measuring data can be displayed and evaluated elsewhere. A flexible decentralized monitoring system also enables the analysis of measuring signals and monitoring of the plants by external providers. A user-orientated service ensuring the quantitative evaluation of changes in the oil-machine system, including the recommendation of resulting preventive maintenance measures, relieves plant operators, increases reliability and saves costs.

In a web-based decentralized online oil condition monitoring system, the sensor signals are preferably transferred through the Internet to a database server and recorded on an HTML page as user interface [5].

Following authentication, a simple web browser permits access via the wired or

wireless LAN. In case of alarm signals, an immediate automated generation of warning messages, for instance by e-mail or SMS, is possible from any computer with Internet connection. Figure 10 shows the WearSens® sensor with 1" connector block for rough environment [6,7].
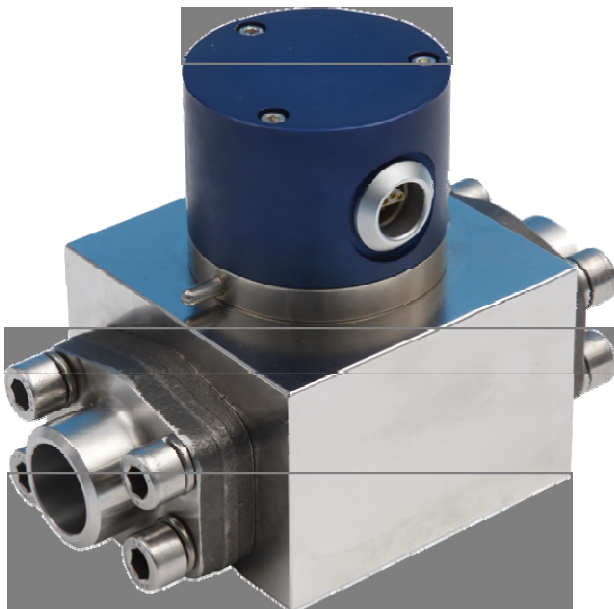
Figure 10. Sensor with 1" connector block

6. SUMMARY

The online diagnostics system measures components of the specific complex impedance of oils. For instance, metal abrasion due to bearing wear at the tribological contact, broken oil molecules, acids or oil soap cause an increase in electrical conductivity that directly correlates with the degree of pollution of the oil. The dielectrical properties of the oils are especially determined by the water content, which, in the case of products that are not enriched with additives, becomes accessible by an additional accurate measurement of the dielectric constant. In the case of oils enriched with additives, statements on the degradation of additives can also be deduced from recorded changes in the dielectric constant.

Indication of damage and wear is measured as an integral factor of, e.g., the degree of pollution, oil aging and acidification, water content and the decomposition state of additives or abrasion of the bearings. It provides informative data on lubricant aging and material loading as well as the wear of the bearings and gears for the online operative monitoring of components of machines. Additional loading, for instance, by vibration induced mixed friction in rolling-sliding contact (rolling bearings, gears, cams, etc.) causes faster oil aging. Verified in roller bearing rig tests, the oil suffers from incipient resinification and significant acidification, as proven by infrared spectroscopy of used lubricant.

For an efficient machine utilization and targeted damage prevention, the new WearSens® online condition monitoring system offers the prospect to carry out timely preventative maintenance on demand rather than in rigid inspection intervals. The determination of impurities or reduction in the quality of the lubricants and the quasi continuous evaluation of the bearing and gear wear and oil aging meet the holistic approach of a real-time monitoring of a change in the condition of the oil-machine system.

The measuring signals can be transmitted to a web-based condition monitoring system via LAN, WLAN or serial interfaces of the sensor system. The monitoring of the tribological wear mechanisms during proper operation below the tolerance limits of the components then allows preventive, condition-oriented maintenance to be carried out, if necessary, long before regular overhauling, thus reducing outages caused by wear while simultaneously increasing the overall lifetime of the oil-machine system.

The oil sensor system was installed into an oil circuit of a hydraulic actuator system for ground resonance excitation performing a long term analysis of the hydraulic oil quality. The functionality of the introduced electric online condition monitoring sensor system is tested successfully. The evaluation of the experiment is presented.

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