Condition Based Maintenance of Wind Turbines by 24 / 7 Monitoring of Oil Quality, Oil Aging and Additive Consumption: Identification of critical operation conditions & determination of the next oil exchange

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Abstract
The innovative approach of the oil sensor system is presented for the continuous, online measurement of wear in hydraulic systems, industrial gears, generators, turbines and transformers. The electrical conductivity, relative permittivity and temperature are measured with a high precision and low noise over a broad range to enable the detection of small changes in the oil induced by variations in the tribology of the device under test. By the high sensitivity of the time measurement method the sensor system detects critical operation conditions much earlier than existing technologies such as vibration measurement or particle counting. A new parameter the WearSens® Index (WSi) is introduced. The mathematical model of the WSi combines all measured values and its gradients in one single parameter for a comprehensive monitoring to prevent wind turbines from damage. WSi enables a long term prognosis on the next oil change by 24/7 server data logging. Furthermore, corrective procedures and/or maintenance can be carried out before actual damage occurs. Efficient machine utilization, accurately timed preventive maintenance, a reduction of downtime and an increased service life and can all be achieved. First WSi results of an onshore wind turbine installation compared to traditional vibration monitoring are shown.

Keywords:
Oil sensor system, oil aging, bearing wear, online condition monitoring, preventive maintenance, oil additive degradation, white etching cracks, industrial gearboxes, critical vibration loading.

1 BASIC PRINCIPLES OF THE SENSOR SYSTEM
1.1 Base sensor concept
Components of the complex impedances X of oils, in particular the specific electrical conductivity $\kappa$ and the relative permittivity $\varepsilon_r$ as well as the oil temperature $T$ are measured with the presented oil sensor system [1-3]. The values $\varepsilon_r$ and $\kappa$ are determined independently of each other.

Abrasive (metallic) wear, ions, broken oil molecules, acids, oil soaps, etc., cause an increase of the oil conductivity $\kappa$. 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. Oils are principally electrical non-conductors. The electrical residual conductivity of pure oils lies in the range below 1 pS/m. A direct connection between the degree of contamination of oils and the electrical conductivity 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, which are reflected in the relative permittivity [4, 5].

To measure the electrical conductivity and the dielectric constant the oil is passed through an electrode array, which determines the electrical resistance and the capacitance of the sensor assembly using the base oil as a resistive material and dielectric. Figure 1 shows a detail picture of the sensor electrode array with the triple plate design [6].

For a description of electrical conductivity, Ohm’s law is first considered in differential form [7].

$$d\vec{I} = \left( \begin{array}{c} \frac{\kappa}{d\vec{E}} \frac{dU}{dz} \\ \frac{\kappa}{d\vec{E}} \frac{dU}{dy} \\ \frac{\kappa}{d\vec{E}} \frac{dU}{dx} \end{array} \right) = \left( \begin{array}{c} \frac{dI_x}{dx} \\ \frac{dI_y}{dy} \\ \frac{dI_z}{dz} \end{array} \right) = \kappa \cdot \vec{E}$$

$$d\vec{I} : \text{differential current,}$$
$$d\vec{U} : \text{differential voltage,}$$
$$\vec{j} : \text{current density,}$$
$$\vec{E} : \text{electric field strength,}$$
$$d\vec{x}, d\vec{y}, d\vec{z} : \text{differential path elements,}$$
$$\kappa : \text{electrical conductivity.}$$
With the generalized Ohm’s law for an isotropic medium

\[ \mathbf{J} = \kappa \cdot \mathbf{E}, \quad \kappa = \frac{1}{\rho} \quad (2) \]

\((\rho: \text{resistivity})\) and the basic equation for the electric field, analogous to Ohm’s law in differential form is valid for the electric displacement in an isotropic medium [8]:

\[ \mathbf{D} = \varepsilon_0 \cdot \varepsilon_r \cdot \mathbf{E} \quad \text{(3)} \]

with:

- \(\mathbf{D}\): dielectric displacement,
- \(\varepsilon\): dielectric permittivity,
- \(\varepsilon_0\): vacuum permittivity,
- \(\varepsilon_r\): relative permittivity.

So the desired parameters \(\kappa\) and \(\varepsilon_r\) can be determined by the measurement of voltages or currents.

### 2 TEMPERATURE COMPENSATION

Ion mobility and thus, electrical conductivity \(\kappa\) are dependent on the internal friction of the oil and therefore, also on its temperature. The conductivity \(\kappa\) 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 [9].

Calculating the electrical conductivity and the dielectric constant at the reference temperature of 40° Celsius is realized by approximating the polynomial form of the temperature dependence.

\[ \kappa_{T_0} = \kappa_{T_{0a}} + (a\Delta T_i + b\Delta T_i^2 + c\Delta T_i^3) \cdot \kappa_m \quad (4) \]

\(\kappa_{T_{0a}}\) is the approximate electrical conductivity of the oil at the reference temperature \(T_0\). \(\kappa_{T_{0a}}\) is the previously calculated (old) electrical conductivity at the reference temperature \(T_0\). \(\kappa_m\) is the non-temperature compensated measured value of the electrical conductivity, \(a, b, c\) are the coefficients of the approximating polynomial to be adaptively determined.

\[ \Delta T_i = T_0 - T_i \quad (5) \]

is the temperature difference. The approximation by a polynomial of third degree guarantees a good approximation at a reasonably low computational effort for the microcomputer used. For the determination of the coefficients of the polynomial a risk function is defined on the basis of the Gaussian method of least squares from the \(N\) measured values pairs and the approximating polynomial, whose minimization enables determination of the desired coefficients. Figure 2 shows the basic method.

**Figure 2:** Demonstration graph of the Gaussian least squares method.

Figure 3 shows the effect of temperature compensation of the electrical conductivity. The algorithm needs about 10 initial measurements to start the compensation and gets more precise after a short time. While the conductivity \(\kappa\) changes significantly with temperature, the temperature compensated conductivity \(\kappa_{40}\) stays nearly constant. The implemented adaptive algorithm can now work in the background of the measurement procedure autonomously; it has to be reset only after an oil exchange to adapt to the new lubricant. Without the adaptive temperature compensation it is not possible to identify any critical operation conditions in the monitored system due to the high influence of the temperature on the conductivity and the relative permittivity [10].

**Figure 3:** Graph of the measured and compensated electrical conductivity at a reference temperature of 40 °C.

### 3 MATHEMATICAL MODEL OF THE WEARSSENS® INDEX – WS

The WearSens® Index (WS) has originally been developed for the lubricant analysis of a wind turbine gearbox, however it can be adapted to any other lubricated system and different oil types with small modifications. The following description is based on the wind turbine application.

The WS model considers short, mid and long-term changes in the lubricant by continuous monitoring of the conductivity, relative permittivity and temperature over a time period of several years with a high time resolution of < 1 minute. Because of the measurement sensitivity and the high time resolution critical operation conditions can be
identified much earlier and a damage can be evaded in short term analysis. The stress of the lubricant and the turbine itself is based on the actual wind condition, wind fluctuation and wind turbine settings (e.g. pitch control, torque control) resulting in instantaneous changes of the conductivity and relative permittivity and their gradients. Frequent critical operation conditions lead to faster degradation of the oil additive complex. The hypothesis is, that the consumption of the additives is directly correlated with the reduction of the relative 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. Critical operation conditions result in an increased charge carrier generation and will change the conductivity and its gradient significantly. After identifying initial base \( \kappa_{40i} \), \( \varepsilon_{40i} \), \( \Delta \kappa_{40i} \) and \( \Delta \varepsilon_{40i} \) the compensated data of \( \kappa_{40} \), \( \varepsilon_{40} \) can be feed into the WS, model below:

\[
WS_i = \int_{T_1}^{T_2} \left[ f(\kappa_{40}), \kappa_{40} \right] + f(\varepsilon_{40}, \varepsilon_{40}) + f(\Delta \kappa_{40}, \Delta \varepsilon_{40}) + f(\Delta \kappa_{40}, \Delta \varepsilon_{40}) + f(T, T) \, dt
\]  

(6)

A simulated wind power profile over a time of ten years is depicted in figure 4 including cyclic high and low wind conditions. The corresponding continuous decrease of the WS due to the varying load conditions and the resulting degradation of the oil is schematically shown in the dashed green line. From this point, the benefits of a condition based oil change are clearly eminent: an offshore oil exchange is performed every 5 years independent of the actual oil quality. By using the WS as an indicator for the oil change on demand – condition based – the time interval of the oil exchange can be increased quite a lot due to the real condition of the oil; this will save money as a direct effect to the wind park owner, preserve environment and resources. Furthermore, the short-term analysis can avoid critical operation conditions and prevent the wind turbine from damage.

4 SENSOR INSTALLATION ON WIND TURBINE: WSI AND VIBRATION MONITORING

This section demonstrates first results of the 24/7 oil condition monitoring of an onshore wind turbine installation with WearSens®. The data of the existing vibration condition monitoring system was compared to the recorded WS data (see figure 5). The data was recorded in November 2015. The WS data in figure 5 is visualized at low (green curve) and high time resolution (blue curve), to show the high information density available at maximum time resolution.

![Figure 4: Time course of the simulated WearSens® Index WS and wind power profile over 10 years.](image)

![Figure 5: Time course (24 hours) of WS with low time resolution (green), WS high time resolution (blue) and the vibration signal (red).](image)

The data of the vibration monitoring (red curve) can be compared to the WearSens® index data over a 24 hour time scale: the changes in the oil identified by the WS, due to load and overload conditions are much earlier than the vibration monitor can signal, so it is possible to react much faster on critical conditions to prevent the gearbox and the components from damage to enhance the overall life time. By the long term analysis over several month and years it is possible to perform condition based maintenance and a condition based oil change only when it is necessary to preserve the environment, to protect the oil resources and to reduce costs.

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 qualitative 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 [4]. 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.
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\textsuperscript{®} online condition monitoring system and the WearSens\textsuperscript{®} index 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 oil sensor system has been installed into an onshore wind turbine performing short and long-term analysis of the lubricant quality. The recorded data confirm the actual WearSens\textsuperscript{®} Index model.

7 REFERENCES


The oil sensor system has been installed into different onshore wind turbines performing short and long-term analysis of the lubricant quality. The recorded data confirm the actual WearSens\textsuperscript{®} Index model.