Identification of Critical Operation Conditions of Industrial Gearboxes by 24/7 Monitoring of Oil Quality, Oil Aging, and Additive Consumption

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Abstract. The demand for wind energy grows at exponential rates. At the same time improving reliability, reduced operation and maintenance costs are the key priorities in wind turbine maintenance strategies [1]. This paper provides information about a novel online oil condition monitoring system to give a solution to the mentioned priorities. The presented sensor system enables damage prevention of the wind turbine gear-box by an advanced warning time of critical operation conditions and an enhanced oil exchange interval realized by a precise measurement of the electrical conductivity, the relative permittivity and the oil temperature. 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. Furthermore, the WSi enables a long-term prognosis on the next oil change by 24/7 server data logging. Corrective procedures and/or maintenance can be carried out before actual damage occurs. First WSi results of an onshore wind turbine installation compared to traditional vibration monitoring are shown.

1. Introduction
In general, the field of maintenance can be divided into three sectors: preventive (time-based), intelligent (condition-based) and reactive maintenance (run to failure), which show different dependencies between costs and number of failures. Figure 1 shows the costs associated with the different strategies [1].

![Figure 1. Costs associated with traditional maintenance strategies [1].](image-url)
From this graph, the optimal point in terms of costs and number of failures can be identified within the center of the intelligent maintenance sector; intelligent maintenance can be realized with an online condition monitoring solution. Different kinds of online monitoring systems have been established over the past years: temperature [2, 3, 3], vibration [4] and particle counting [1, 5]. A vibration monitoring system analyses changes in the frequency spectrum of the observed bearing/gearbox component by Fast Fourier Transformation by converting a time-domain signal into a frequency-domain signal [6]. An optical particle-counter can detect particles larger than 4µm due to the optical resolution of the laser light source. All of these systems need a significant change in the topological contact surfaces, which means damaged surfaces, particles and pitting.

The presented oil sensor system in contrast is already sensible at the very beginning of the damage formation stage, when the tribological layer gets depleted due to over-load conditions. At this early stage, an increase of electrical charge carriers can be identified by the oil sensor system WearSens®: 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 [9]. Inorganic compounds occur at con-tact surfaces from the wear of parts, broken oil molecules, acids or oil soaps. These all lead to an increase in the electrical conductivity, which correlates directly with the wear. In oils containing additives, changes in dielectric constant infer the chemical breakdown of additives. A reduction in the lubricating ability of the oils, the determination of impurities, the continuous evaluation of the wear of bearings and gears and the oil aging all together follow the holistic approach of real-time monitoring of changes in the oil-machine system [10, 11]. 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 one pS/m. A direct connection between the degree of contamination of oils and the electrical conductivity is found. An in-crease 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 [12, 13].

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 2 shows a detail picture of the sensor electrode array with the triple plate de-sign and the schematic electronic circuit. By the high sensitivity of a time measurement method the sensor system detects critical operation conditions much earlier than existing technologies such as vibration measurement or particle counting [14].

![Figure 2](image.png)

**Figure 2.** Detail of the triple plate design of the WearSens® base sensor and the corresponding simplified drawing of the electronic circuit.
To determine the conductivity and permittivity with a direct measurement of AC observables in a RC circuit is quite inaccurate, because oil has a very high resistance $R$ (several $G\Omega$) and a very low capacity $C$, which leads to high uncertainties, errors and a low resolution, which is necessary to follow the effects in oil. In the presented system, the electrical conductivity $\kappa$ and relative permittivity $\varepsilon_r$ are determined by a precise time measurement with a very high accuracy and repeatability based on an integrating measurement technique with a high time / bandwidth product: the measurement range for the conductivity starts from $0.1\ \text{pS/m}$ up to $1,000,000\ \text{pS/m}$ with a resolution of $0.01\ \text{pS/m}$; the relative permittivity is measured between 1 and 5 with a resolution of $1*10^{-6}$.

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 \[16\]. 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.

$$\kappa_{T_0} = \kappa_{T_0a} + (a\Delta T_i + b\Delta T_i^2 + c\Delta T_i^3) \cdot \kappa_m$$

$\kappa_{T_0}$ 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, $a$, $b$ and $c$ are the coefficients of the approximating polynomial to be adaptively determined during the runtime of the sensor system.

$$\Delta T_i = T_0 - T_i$$

is the temperature difference.

Figure 3. Electrical conductivity versus temperature with second and third order fit curves.
Figure 3 shows the dependency of the electrical conductivity with the temperature of a gearbox oil. Two different trend lines with second order fit and third order fit are plotted on the measured data. The approximation by a polynomial of third degree guarantees a good approximation at a reasonably low computational effort for the used microcomputer with an optimal coefficient of determination $R^2$. For the adaptive determination of the coefficients $a$, $b$ and $c$ 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 4 shows the effect of the adaptive temperature compensation of the electrical conductivity. The algorithm needs about 10 initial measurements to start the compensation and is getting more precise after a short time.

![Graph of the measured and compensated electrical conductivity at a reference temperature of 40 °C.](image)

While the measured 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 [17].

3. Mathematical model of the WearSens® Index – $W_S$

The WearSens® Index ($W_S$) 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 individual modifications. The following description is based on the wind turbine application.

The $W_S$ 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 < 45 seconds. 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. Critical operation conditions result in an increased charge carrier generation and will change the conductivity and its gradient significantly. A big change in a short time period in the measured values leads to a high WS\text{signal}; for example, a significant increase in the electrical conductivity in a short time period is an indication of an abrupt high load or depending on the increase in the conductivity a critical operation condition. 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 relative permittivity $\varepsilon_r$ is directly affected by the presence of polar elements; there is a high content of polar additives in gearbox oils [7]. The polar additives combine together with other polar elements (e.g. wear products, water contamination), so from this point of view the consumed additives are not polar anymore, which results in the reduction of the relative permittivity. 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. After identifying initial base $\kappa_{40}$, $\varepsilon_{r40}$, $\Delta\varepsilon_{ir40}$, $\Delta\kappa_{40}$, $T_i$ can be feed into the simplified WS\text{model below:}

$$WS_i = \int_{t_1}^{t_2} \left[ f(\kappa_{40}, \kappa_{i40}) + f(\varepsilon_{r40}, \varepsilon_{ir40}) + f\left(\frac{\Delta\varepsilon_{r40}}{\Delta t}, \frac{\Delta\varepsilon_{ir40}}{\Delta t}\right) + f\left(\frac{\Delta\kappa_{40}}{\Delta t} \Delta\kappa_{i40}\right) + f(T, T_i) \right] dt$$

A simulated wind power profile over a time of ten years is depicted in figure 5 including cyclic high and low wind conditions.

![Time course of the simulated WearSens® Index WS\text{and wind power profile over 10 years.}](image)

**Figure 5.** Time course of the simulated WearSens® Index WS\text{and wind power profile over 10 years.}

The corresponding continuous decrease of the WS\text{, 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\text{, 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 a wind turbine: WS\textsubscript{i} and vibration monitoring

This section demonstrates first results of the 24/7 oil condition monitoring of an on-shore wind turbine installation with WearSens\textsuperscript{®} in the cooling bypass of a Südwind S77, Winergy (FAG gearbox), 3MW. Figure 6 below shows the onshore wind turbine, the wind turbine gearbox in the nacelle and the installed base sensor.

![Figure 6](image)

**Figure 6.** a) picture of the onshore wind turbine in Büddenstedt, Germany, b) preparation at the gearbox for the WearSens\textsuperscript{®} base sensor installation and c) the installed base sensor in the existing cooling bypass.

The onshore wind turbine was equipped with an existing vibration monitoring system. More general information on the computation, limitations and analysis of the vibration data can be found in the literature [1, 4, 6, 8].

The time course of the vibration monitoring data and the normalized WS\textsubscript{i} data, recorded on 14th of November 2015, was compared in figure 7; the WS\textsubscript{i} data is plotted in green colour at low and in blue colour at high time resolution, to demonstrate the high information density available at an average update rate of less than 45 seconds. The orange curve shows the dimensionless CMI data, which trend is interpreted as abnormal shifts in the cycling frequencies of the bearing on the fast shaft; here the warning level was set at CMI=50 and the alarm level at CMI=100 from the vibration CMS manufacturer.

The data of the WS\textsubscript{i} at low time resolution has a similar signal sequence as the vibration data, but at a different time base: the peaks in the WS\textsubscript{i} signal are significantly in front of the vibration signal, provided from the vibration-monitoring operator. Based on an empirical approach the hypothesis is, that fluctuations from normal to critical operation conditions can be identified earlier with the presented online oil sensor system by the precise measurement of the electrical conductivity and relative permittivity, because changes in the tribological layer, an increased charge carrier generation occurs before changes in the vibration signal of gearbox components due to material fatigue. Therefore, it is possible to react much faster on events of critical conditions to prevent the gearbox 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 oil change on demand to preserve the environment, to protect the oil resources and to reduce costs.
5. Conclusion

The online diagnostics system measures components of the specific complex impedance of oils. The indication of forming stage 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, which is correlated to the changes in the electrical conductivity and relative permittivity. By the adaptive temperature compensation of the measured values, it is possible to identify even small variation in the actual charge carrier generation and additive consumption. For an efficient machine utilization and targeted damage prevention, the WearSens® online condition monitoring system and the WearSens® index offers the prospect to carry out timely preventative maintenance on demand rather than in rigid inspection intervals. The benefits of an extended oil change interval are reduced costs, preservation of the environment and resource protection. The oil sensor system has been installed into an onshore wind turbine performing short and mid-term analysis of the lubricant quality in a time period of 360 days. The direct advantages of this online oil condition online monitoring are detection of critical operation conditions and damage prevention to increase the lifetime of gearbox. The high time resolution, fast response time and accuracy of WearSens® allows earlier intervention control / optimization of the current operation in comparison to sole vibration analysis.

6. References

[1] P. Tchakoua, R. Wamkeue, M. Ouhrouche, F.S. Hasnaoui, T.A. Tameghe, G. Ekemb: Wind Turbine Condition Monitoring: State-of-the-Art Review, New Trends, and Future Challenges, Energies 2014, 7, pp. 2595-2630, (2014)
[2] C.J. Hellier: Handbook of Non-destructive Evaluation, McGraw-Hill Professional Publishing, New York, USA, (2003)
[3] J.-Y. Park, J.-K. Lee, K.-Y. Oh, J.-S. Lee, B.-J. Kim: Design for 3MW Wind Turbine and its Condition Monitoring System, Proceedings of the International Multi Conference of Engineers and Computer Scientists, IMECS 2010, Kowloon, Hong Kong, 17–19 March 2010, Volume II, pp. 930–933, (2010)

[4] B.N. Madsen: Condition Monitoring of Wind Turbines by Electric Signature Analysis, Master’s Thesis, Technical University of Denmark, Copenhagen, Denmark, October 2011, (2011)

[5] A.C. Goncalves, J.B. Campos: Predictive maintenance of a reducer with contaminated oil under an eccentric load through vibration and oil analysis, J. Braz. Soc. Mech. Sci. Eng. 2011, 33, 1–7, (2011)

[6] M.M. Khan, M.T. Iqbal, F. Khan: Reliability and Condition Monitoring of a Wind Turbine, Proceedings of the 2005 Canadian Conference on Electrical and Computer Engineering, Saskatoon, SK, Canada, 1–4 May 2005, pp. 1978–1981, (2005)

[7] Noria Corporation: The critical role of additives in lubrication, Machinery Lubrication June 2012, (2012)

[8] A. Jablonsky, T. Barszcz, M. Bielecka: Automatic validation of vibration signals in wind farm distributed monitoring systems, Measurement 2011, 44, 1954–1967, (2011)

[9] M. Mauntz and U. Kuipers: Ölsensorsystem- Sensorsystem zur Messung von Komponenten der komplexen Impedanz elektrisch gering leitender und nichtleitender Fluide, dessen Realisierung und Anwendung, patent application no. 10 2008 047 366.9, German Patent Office, Munich, (2008)

[10] M. Mauntz and U. Kuipers: Verfahren, Schaltungsanordnung, Sensor zur Messung physikalischer Größen in Fluiden sowie deren Verwendung, European patent application no. EP 09000244, European Patent Office, Munich, (2009)

[11] M. Mauntz, J. Gegner and U. Kuipers: Ölsensorsystem zur Echtzeit-Zustandsüberwachung von technischen Anlagen und Maschinen, Technisches Messen 77, pp. 283-292, (2010)

[12] M. Mauntz, U. Kuipers and J. Gegner: New Electric Online Oil Condition Monitoring Sensor – an Innovation in Early Failure Detection of Industrial Gears, The 4th International Multi-Conference on Engineering and Technological Innovation July 19th – July 22nd, 2011, Orlando, Florida, USA 2011, Proceedings Volume I, International Institute of Informatics and Systemics, Winter Garten, FL, USA, 2011, pp. 238-242, (2011)

[13] M. Mauntz, U. Kuipers and J. Gegner: High-precision online sensor condition monitoring of industrial oils in service for the early detection of contamination and chemical aging, Sensor + Test Conf., 7.-9.6.2011, Nürnberg, AMA Service GmbH, Wunstorff, pp. 702-709, (2011)

[14] M. Mauntz, J. Gegner, S. Klingauf and U. Kuipers: Continuous Wear Measurement in Tribological Systems to Control Operational Wear Damage with a new Online Oil Sensor System, TAE Technische Akademie Esslingen, 19th International Colloquium Tribology, Esslingen, January 21-23, 2014, (2014)

[15] A. Saeed: Online Condition Monitoring System for Wind Turbine, Master’s Thesis, Blekinge Institute of Technology, Karlskrona, Sweden, (2008)

[16] M. Mauntz, U. Kuipers and J. Peuser: Continuous, online detection of critical operation conditions and wear damage with a new oil condition monitoring system, WearSens®, 14th International Conference on Tribology - SERIATEB’15 Proceedings, Belgrad, Serbian Tribology Society Kragujevac, University of Belgrade, Faculty of Mechanical Engineering, Belgrade, ISBN: 978-86-7083-857-4, S. 283-288, (2015)

[17] M. Mauntz, U. Kuipers and J. Peuser: New oil condition monitoring system, WearSens® enables continuous, online detection of critical operating conditions and wear damage, Malaysian International Tribology Conference 2015 - MITC2015, Penang, Malaysia on November 16-17, 2015, Conference Proceedings, ISBN: 978-967-13625-0-1, S. 179-180, (2015)

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