Deep online analysis of dielectric parameters for lubricant oils with an innovative oil sensor system: Identification of critical operation conditions of wind turbine gearboxes for reduction of failure rates and live time enhancement

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RESUMO

A demanda por energia eólica cresce a taxas exponenciais. Confiabilidade e eficiência operacional são as principais prioridades em turbinas eólicas para estratégia da manutenção. O objetivo deste material é apresentar e fornecer um novo sistema de monitoramento de óleo on-line com intuito de atender as prioridades vigentes. Este sistema mensura, além de temperatura, os componentes das impedâncias *complexas X* de cada óleo, como condutividade elétrica e constante dielétrica relativa. Através do monitoramento dos dados críticos e programação de alarmes, o sistema viabiliza troca de óleo baseado em condições reais que consequentemente garantem eficiência e segurança na operação das turbinas eólicas. Adicionalmente aos parâmetros previamente mencionados, o equipamento apresenta um parâmetro exclusivo - o Índice WearSens ® (WS i). Este índice é baseado em um modelo matemático *WS i* que reúne todos os valores medidos e seus gradientes em um único monitoramento. Além disso, o *WS i* permite através de medição contínua um prognóstico de longo prazo para próxima troca de óleo, afim de que as intervenções ocorram de forma eficiente e no tempo adequado. Os valores reais do monitoramento WS i incluindo sua base de cálculo são apresentados aqui como resultados da aplicação. Os dados foram coletados de dois sistemas com óleos distintos instalados em turbinas eólicas on shore atualmente em operação. Os valores de curto prazo e longo prazo apresentam significativas tendências e eventos, fatos que também serão dicustidos neste trabalho detalhadamente. Por monitoramento e análise contínua do qualidade do óleo, é possível identificar o intervalo de tempo ideal baseado em condições reais para próxima troca de óleo. O sistema impacta significativamente em redução de custo de manutenção quando o óleo é monitorado e permanece estável e totalmente funcional.

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. This presentation provides information about a new online oil condition monitoring system to give a solution to the mentioned priorities. The oil sensor system measures oil temperature and oil components of complex impedances X, in particular electrical conductivity and relative dielectric constant. The sensor system enables damage prevention of the wind turbine gearbox by an advanced warning time of critical operation conditions and an enhanced oil exchange interval realized by precise measurements. 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. 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. Raw data and WSi results of several wind turbine installations with different lubrication oils are shown. Short-term and long-term analysis of the data show significant trends and events, which are discussed more in detail. By long-term monitoring and continuous analysis of the oil quality, it is possible to identify the optimal and condition based time interval of the next oil exchange. The system results in enormous cost reduction in wind turbine operation, once the oil is monitored and remains stable and fully functional.

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]. 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].
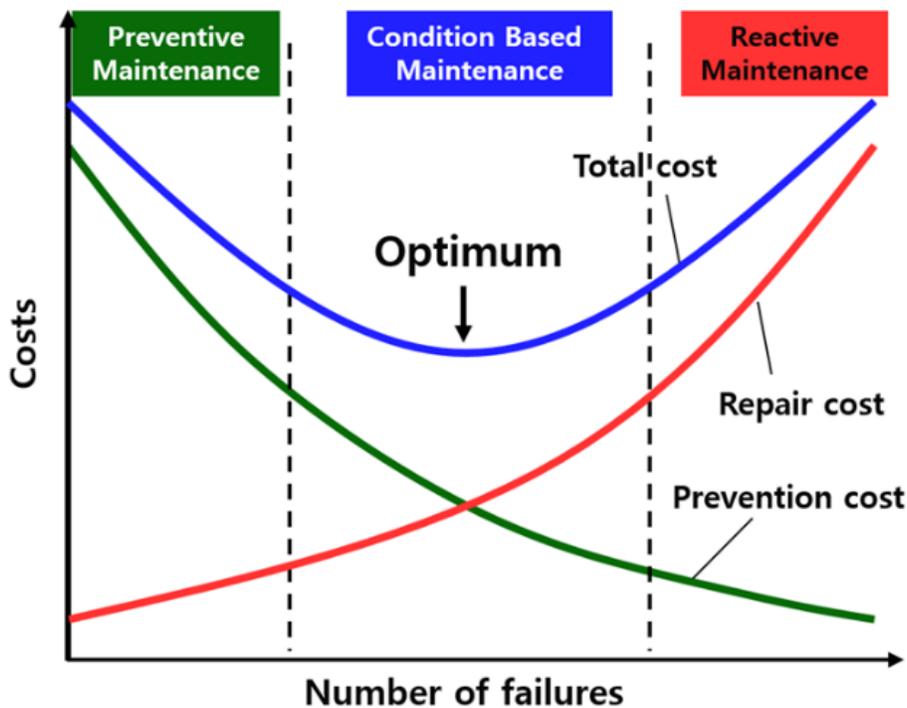

Figure 1. Costs associated with traditional maintenance strategies [1].

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 overload 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 contact 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 electrical conductivity kappa. It rises with increasing ion concentration and mobility. The electrical conductivity of almost all impurities is high compared to 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 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 epsilon r [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 design 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.
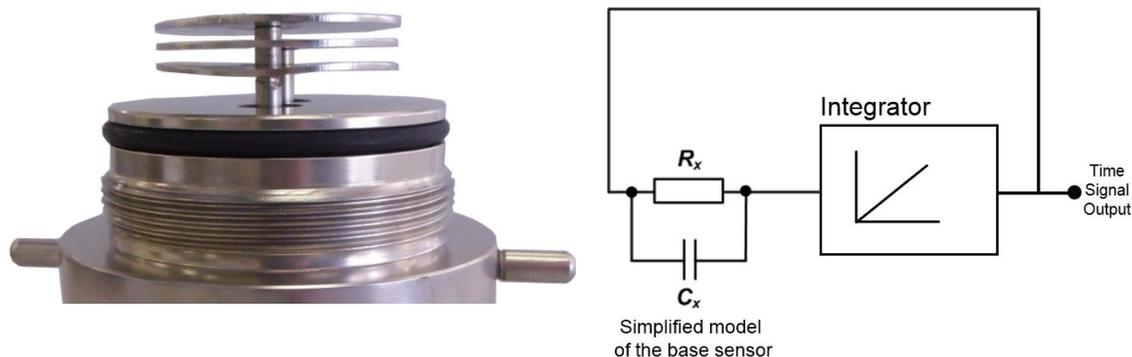

Figure 2. Detail of the triple plate design of the WearSens® base sensor and the corresponding simplified drawing of the electronic circuit.

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 GOhm) 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 epsilon 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 pS/m up to 1,000,000 pS/m with a resolution of 0.01 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 [13]. 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.

$$\kappa_{T0} = \kappa_{T0a} + \left(a\Delta T_i + b\Delta T_i^2 + c\Delta T_i^3\right) \cdot \kappa_m$$

κ_{T0} is the approximate electrical conductivity of the oil at the reference temperature T0, κ_{T0a} is the previously calculated (old) electrical conductivity at the reference temperature T0, κ_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.

$\Delta T_i = T_0 - T_i$
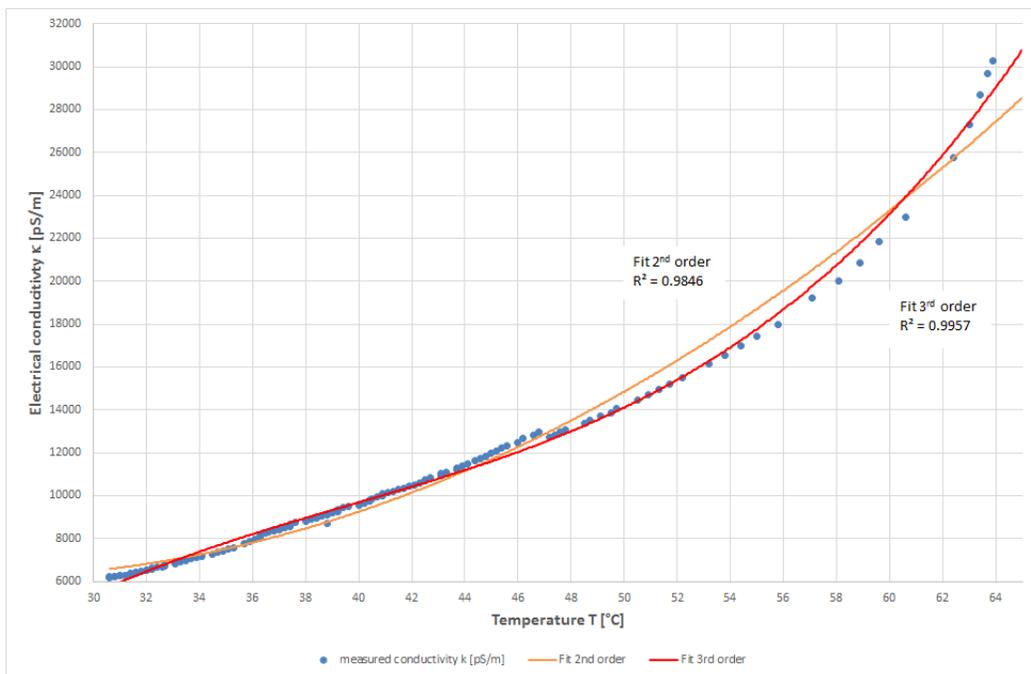is the temperature difference.

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 using the example of field data from an onshore wind turbine: the wind fluctuations are changing the oil temperature and with it the electrical conductivity permanently.
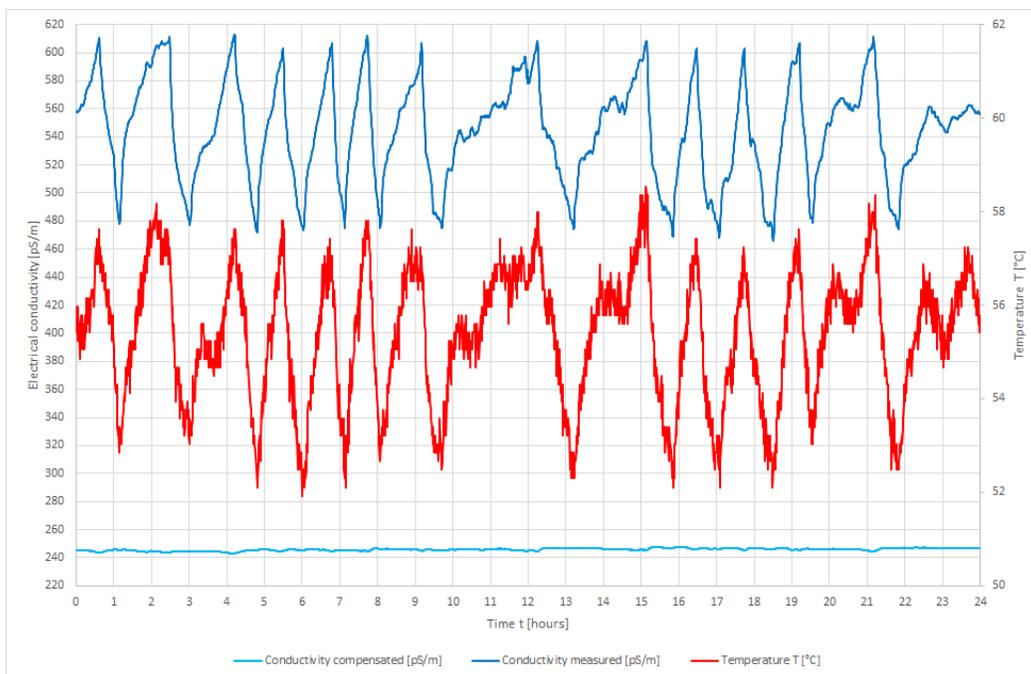

Figure 4. Graph of the measured and compensated electrical conductivity from an onshore wind turbine at a reference temperature of 40 °C.

While the measured conductivity κ changes significantly with temperature, the temperature compensated conductivity κ_{40} stays nearly constant. The implemented adaptive algorithm is working 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 a critical operation condition 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 – WS$_I$

The WearSens® Index (WS$_i$) 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 WS$_i$ 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$_i$ 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 ε_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 κ_{i40}, ε_{ir40}, $\Delta\varepsilon_{ir40}$, $\Delta\kappa_{i40}$, T_i can be feed into the simplified WS$_i$ model below:

$$
WS_i = \int_{t1}^{t2} \Bigg[f(\kappa_{40}, \kappa_{i40}) + f(\varepsilon_{r40}, \varepsilon_{ir40}) \\
+ f\left(\frac{\Delta\varepsilon_{r40}}{\Delta t}, \Delta\varepsilon_{ir40}\right) + f\left(\frac{\Delta\kappa_{40}}{\Delta t}, \Delta\kappa_{i40}\right) + f(T, T_i) \Bigg] dt
$$

The next pages show results from an offshore installation of the WearSens® sensor system.

4. SENSOR INSTALLATION OFFSHORE WIND TURBINE

This section demonstrates first results of the 24/7 oil condition monitoring of an offshore wind turbine installation with WearSens® in the cooling bypass of a Siemens SWT 2.3MW. Figure 5a below shows the offshore wind turbine, the wind turbine gearbox in the nacelle and the installed base sensor in 5b. The communication unit in 5c transfers the data highly encrypted to the onshore-located data server.

Figure 5. a) picture of the offshore wind turbine, b) WearSens® base sensor installation in the existing cooling bypass and c) sensor communication unit.

The WS_i of two identically constructed offshore wind turbines with the same oil running time are compared in figure 6. From this graph a clear difference between wind turbine WTG #01 and WTG #02 can be identified: this increased WS_i has been reported to the wind farm operator; together with other CMS data a forming damage at the fast drive shaft was identified early enough to prevent the wind turbine for a long downtime and maintenance period due to a total breakdown.

The high dynamics and the high peaks of the WS_i due to the varying load conditions (normal for WTG #01 and overload for WTG #02) and the forming damage in TGW #02 also resulted in the faster degradation of the oil and consumption of the additives, this effect is also visible in the comparative data of the temperature dependency of the electrical conductivity shown in figure 7.

The oil has been changed at the two offshore wind turbines: the data before (red colour) and after the oil exchange (green colour) show a completely different temperature dependency. From this information the active additive level and the oil quality can be determined together with the trending of the WearSens® index WS_i to estimate the next oil exchange condition based by the continuous measurement with the presented oil sensor system.

In figure 7 you see the significant difference between the wind turbine #01 with a normal behaviour and the wind turbine #02 with a forming damage in the grey curve. The additive components are getting consumed much faster due to higher stress and the increased generation of wear products, which results in a decrease of the dependency between the electrical conductivity κ and temperature T.
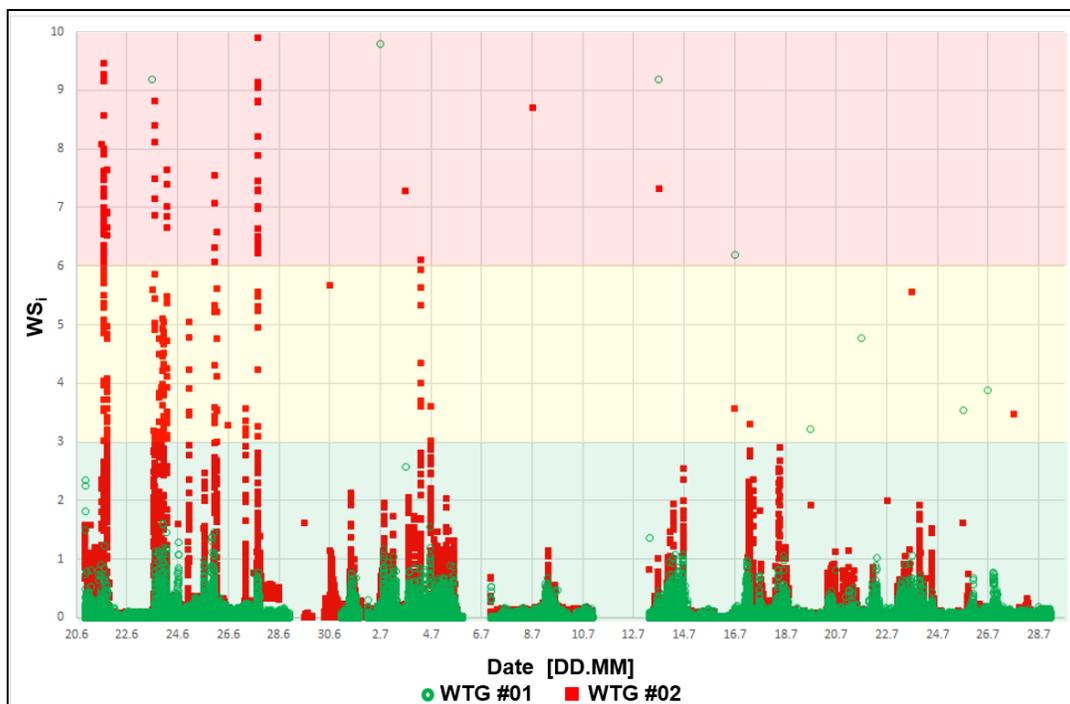
Figure 6. WearSens® Index WS_i profile from two offshore wind turbines with semaphore loading indication.

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 and the computation of the WearSens® index WS_i, because changes in the tribological layer, an increased charge carrier generation occur at the very beginning of a forming damage at 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. From this point of view, the benefits of an online oil condition monitoring are clearly eminent: the short-term analysis can avoid critical operation conditions and prevent the wind turbine from damage; a long term analysis and trending can be used to estimate the time for the next oil change – condition based.
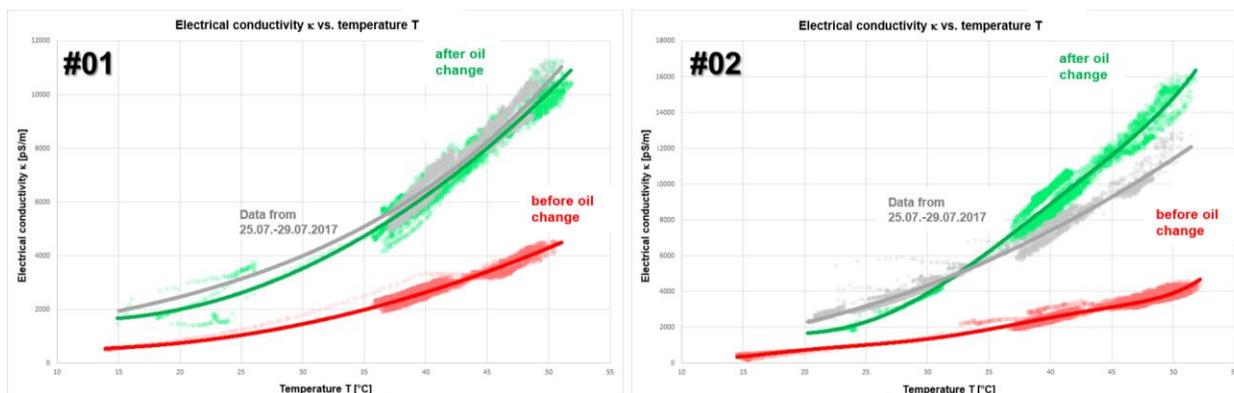

Figure 7: Comparison of the temperature dependency of the electrical conductivity of two offshore wind turbines before, after the oil exchange and after an damage event (turbine #02).

5. CONCLUSION

The online diagnostics system measures components of the specific complex impedance of oils, in particular electrical conductivity and relative dielectric constant are measured. 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. The self - learning adaptive temperature compensation algorithm is essential as the measured parameters not only depend on the temperature but moreover the dependency varies with the type and quantity of the contamination. For an efficient machine utilization and targeted damage prevention, the WearSens® online condition monitoring system and the WearSens® index which one assembles the time dependent gradients of the measured values into one conclusive parameter 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 offshore wind turbine performing short and mid-term analysis of the lubricant quality where together with other CMS data a forming damage at the fast drive shaft was identified early enough to prevent the wind turbine for a long downtime and maintenance period due to a total breakdown. The direct advantages of this online oil condition 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.

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