RENEWABLE ENERGY POWER GRID PROTECTION BY CONTINUOUS, ONLINE CONDITION MONITORING OF OIL AGING IN HIGH VOLTAGE TRANSFORMERS AND OIL REGENERATION SYSTEMS

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**ABSTRACT**

The new sensor system effectively controls the proper operation conditions of high voltage transformers, oil-filled circuit breakers and oil regeneration systems. The online diagnostics system measures components of the specific complex impedance of oils. For instance, contamination during production, formed acids, aldehydes and peroxides, all result in an increase of the electrical conductivity. This directly correlates with the degree of contamination of the oil. This leads to the formation of sludge, which in turn attacks the cellulose insulation, inhibits oil flow and traps heat inside the transformer finally resulting in the destruction of the transformer.

The new OilQSens\textsuperscript{®} measures conductivity $\kappa$, dielectric constant $\varepsilon_r$ and temperature $T$ online and then calculates the breakdown-voltage, loss angle $\tan \delta$ and acidification. It also looks promising to calculate humidity. The new approach utilizes sensor detection of chemical aging of the lubricant and its inhibitors.

Once the oil condition monitoring sensors are installed on the high voltage transformers, or other components such as the oil regeneration system, the measured data can be displayed and evaluated elsewhere. The signals are transmitted to a web-based condition monitoring system via the LAN, WLAN or serial interface of the sensor unit.
Principles of OilQSens®

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

Fig. 1: Basic sensor with triple plate design.

In figure 2 the data acquisition and data processing in the OilQSens® is sketched with the field data acquisition, data processing and signal output.

Fig. 2: Data flow graph of the OilQSens®
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.

Oils are electrical non-conductors. The electrical conductivity of pure oils lies in a range below 0.5 pS/m.

Figure 3 shows conductivities of various materials. The conductivity range of OilQSens® is marked in green. It starts below the conductivity of the distilled water.

![Conductivity of Solids and Fluids](image)

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Fig. 3: Conductivities of liquids and solids

The process of degradation and products of contamination in the oil change the conductivity of insulating oils. Contamination during production or assembly, formed acids, aldehydes and peroxides all bind together and form sludge. Sludge attacks the cellulose insulation, inhibits oil flow and traps heat inside the transformer. It rises with increasing ion concentration and mobility. The electrical conductivity of almost all impurities is high compared with the extremely low conductivity of the original pure oil. A direct correlation 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 contamination of the lubricant.

The hypothesis is to find the moisture by a linear trend line from the changes in the dielectric constant. The loss factor $\tan \delta$ is calculated from the electrical conductivity $\kappa$ and permittivity $\varepsilon_r$, with the dielectric constant $\varepsilon_\infty$ and the angular frequency $\omega = 2\pi f$. 
\[ \tan \delta = \frac{\kappa}{\varepsilon_r \varepsilon_0 \omega} \]

as a function of the proportion of aged oil in the new oil. \(\varepsilon_0\) is the dielectric constant and \(\omega\) is the angular frequency. For temperature-independent representation, directly measured values are converted to temperature-compensated values \(\text{TC}\):

\[ \tan \delta_{\text{TC}} = \frac{\kappa_{\text{TC}}}{\varepsilon_r \varepsilon_{\text{TC}} \varepsilon_0 \omega} \]

Figure 4 shows the loss factor calculated from the measured conductivities \(\kappa\) and dielectric constants \(\varepsilon_r\) of the oil by OilQSens®.

![Graph showing loss factor \(\tan \delta\) as a function of the proportion of aged oil.](image)

**Fig. 4:** Loss factor \(\tan \delta\) as a function of the proportion of aged oil

The dielectric losses in insulating oil are proportional to the loss factor. One use of this monitoring and control system would be to send a warning message when a maximum allowable slope of the temperature-compensated conductivity curve is exceeded and to limit power accordingly. In addition, when a maximum allowable conductivity is exceeded, a warning signal for the implementation of oil maintenance measures, such as an oil filtering in the secondary flow can be generated.
Temperature compensation and measurement accuracy

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. The relative permittivity is measured with the same basic sensor arrangement as used for the determination of the electrical conductivity.

Figure 5 shows the effect of temperature compensation.

![Figure 5: Temperature compensation algorithm](image)

Calculation of the dielectric constant and the conductivity using physics theories for the determination from their physical constants according to Piekara [4] and comparing with the measured values, shows, in permittivity for example, deviations of less than 2% between the measured and the calculated values.

Breakdown voltage and measured electrical conductivity in insulating oils

In a laboratory experiment used transformer oil and new transformer oil were mixed and the breakdown voltage and electrical conductivity measured as a function of the mixing ratios. According to normative standards, the breakdown voltage was measured six times. The following figure shows the solid curves calculated from the measurement results to approximating second degree polynomials.
Fig. 6: Breakdown voltage and measured electrical conductivity as a function of the proportion of ‘used’ transformer oil

The following figure shows the breakdown voltage as a function of the electrical conductivity.

Fig. 7: Breakdown voltage as a function of the electrical conductivity

The measurement of the electrical conductivity is much more accurate and higher resolution than the breakdown voltage. Therefore, the detection of the breakdown voltage by measurement of the conductivity is much more accurate than the direct measurement. While the breakdown voltage varies greatly and is a total of
approximately half the temperature compensated conductivity changes from 1.2 pS/m to 250 pS/m to more than 200 times at a very low standard deviation.

Small deviations from the approximating polynomial of the conductivity are immediately shown in corresponding variations in the dielectric strength. So, for example, the measurement point marked 1 in the diagram shows slightly lower conductivity (due to an interruption of the measurement and inhibitor effects) than the 57% mixing ratio expected, the average of the dielectric strength is increased accordingly at the same time. The same goes for test point 2. In measuring point 3, about 80% aged oil content, the electrical conductivity is higher than expected, according to the mean breakdown voltage rating is lower.

Web-based, decentralized lubricant quality monitoring system

The integration of an online monitoring system with a suitable communication structure offers an interesting practical use 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. high voltage transformers, oil-filled circuit breakers or oil regeneration systems. 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 regeneration 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-transformer 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 via 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 example by e-mail or SMS, is possible from any computer with internet connection. Figure 8 shows the OilQSens® sensor system for high temperatures with communication module.
Summary

The online diagnostics system measures components of the specific complex impedance of oils. For instance, formed acids, aldehydes and peroxides cause an increase in electrical conductivity that directly correlates with the degree of pollution of the oil.

Indication of damage and wear is measured as an integral factor of, e.g., the degree of pollution, oil aging and acidification.

It provides informative data on lubricant aging and formed acids, aldehydes and peroxides, which result in an increase of the electrical conductivity, which then directly correlates with the degree of contamination of the oil as proven by infrared spectroscopy of used lubricants.

For an efficient machine utilization and targeted damage prevention, the new OilQsens® 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 insulated oil and the continuous evaluation of the proper operation conditions of high voltage transformers, oil-filled circuit breakers and oil regeneration systems and oil aging meet the holistic approach of a real-time monitoring of a change in the condition of the oil-transformer system.

The measuring signals of the sensor system are transmitted to a web-based condition monitoring system via LAN, WLAN or serial interfaces. The monitoring of the wear mechanisms during proper operation below the tolerance limits of the insulated oil 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-transformer system.
References


