The aging condition of the insulation has a considerable influence on the life expectancy of the unit

ABSTRACT

Effective lifetime and maintenance management of a transformer fleet requires precise monitoring of the electrical insulation conditions of each transformer. Currently, the condition assessment of the insulating paper of transformers in operation is done indirectly, by oil samples and evaluation of aging markers in the liquid with only limited accuracy. In fact, sampling of the paper for direct analysis of insulation paper quality is only possible when the transformer is under maintenance or decommissioned. In this paper, the methodology and product development of a novel patented optical sensor is presented, which provides a possibility to determine the degree of polymerization (DP) of insulating paper online and in real-time with high precision via optical spectroscopy inside operating transformers. The measurement is carried out non-destructively and within seconds by a specific evaluation of the reflection spectrum of the insulating paper inside the oil or ester filled environment. The investigation has shown that measurement under strongly aged insulating oil is possible, and the medium surrounding the paper has no influence on the determination of the DP-value. Product development involves materials and technologies to ensure long-time accuracy under mechanical, vibrational, chemical, thermal, and electromagnetic challenges of the transformer environment. This novel, innovative sensor is designed to enable online monitoring of the quality of insulating paper in the transformer at various points, like the hotspot, in order to improve operational safety and economical operation. The optical measuring method provides very high reliability and high accuracy. Deviation analysis shows higher accuracy for lower DP-values, which supports the determination of the end-of-life DP-values.

KEYWORDS

aging sensor, degree of polymerization, lifetime management, monitoring, oil-paper insulation, transformer

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An accurate online monitoring of the degree of polymerization would be essential for effective lifetime management of a transformer fleet

Optical sensor for determining the degree of polymerization of the insulation paper inside transformers

1. Introduction

The transformer represents one of the most important assets in the electrical power network so that damage to the asset can have a significant impact on the power supply; therefore, regular condition monitoring, as well as assessment of the transformer, is of great importance [1]. Condition monitoring and evaluation can cover various areas concerning a transformer, whereby the most important field is the condition of the insulation [2]. The aging condition of the insulation has a considerable influence on the life expectancy of the unit [3]. The age-related decomposition of the mostly used oil-impregnated paper insulation considerably limits the life expectancy of a transformer since the mechanical strength of the paper is reduced over time and, as a result, can

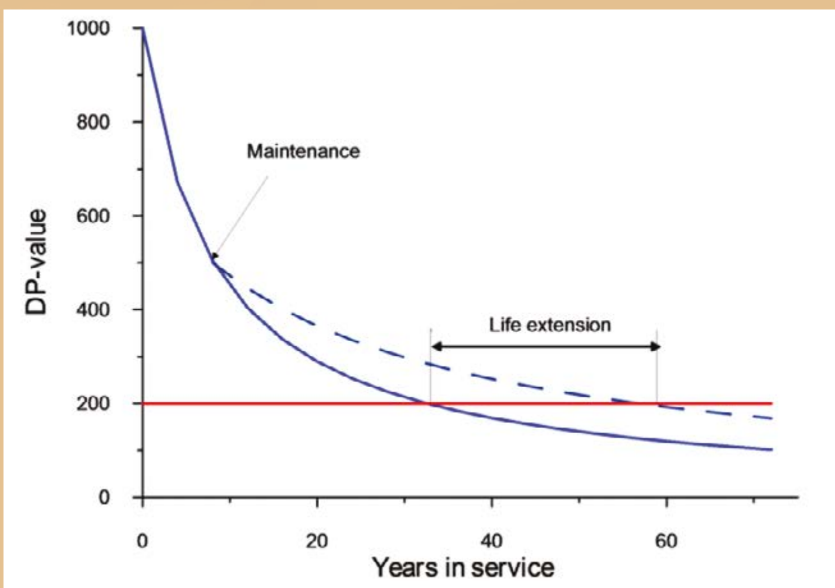

Figure 1. Online monitoring of DP-value for proactive lifetime and maintenance management [6]

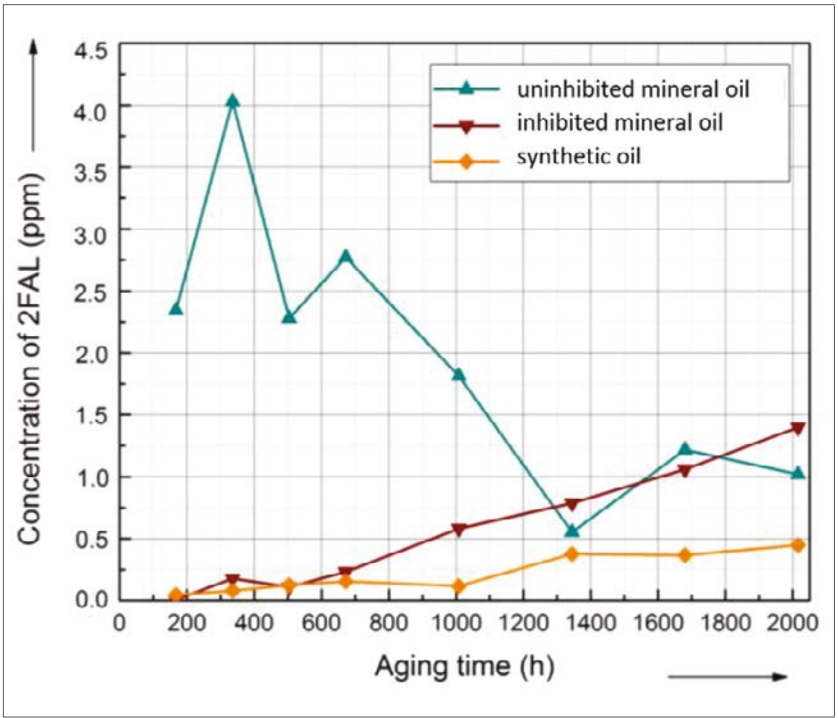

Figure 2. The concentration of furanic compound 2-FAL vs. aging time for different oils in the aging process of oil-paper insulation [11]

no longer withstand failures such as short circuits [4].

In power transformers, insulation paper is commonly based on the various forms of cellulose. Mechanical and electrical performance is depending on the degree of polymerization of cellulose, which is the average number of monomeric units (glucose rings) in the cellulose chain. New insulation paper has a high degree of polymerization with typical DP-values of 1000 or more. The DP-value of 200 is regarded empirically as a threshold value for safe operation and the end of life of the transformer [5].

Therefore, a permanent and accurate online monitoring of the degree of polymerization would be essential for effective lifetime management of a transformer fleet. The fact that in many countries, the transformer population has reached an average age of more than 30 years intensifies the question of the remaining life expectancy determination [6].

Accurate monitoring of DP-values over time, especially at the hottest temperature spot at the coil windings, can reflect the status of the insulation quality. It has to be considered that the solid insulation system is the only part of a transformer

The increase of furanic components is an exclusive indication of thermal aging of the paper, but it cannot exactly deliver the DP-value

that cannot be repaired in an economical way. The end of a transformer's life could be precisely determined by the end-of-life of the paper insulation, and only transformers with the real end-of-life have to be taken out of service. Possible blackouts or accidents might be avoided by exceeding the lifetime of insulation paper, resulting in higher grid stability. Extrapolation and modeling of the data can be used to predict the expected remaining lifetime of transformers. Furthermore, under certain conditions, monitoring of DP-values might trigger the user to perform adequate proactive maintenance actions, e.g., oil drying and / or reclaiming, in order to prolong the transformer's lifetime (Fig. 1).

2. State of the art of determining the aging of solid insulation

There are both indirect and direct methods for the determination of DP-values.

A direct assessment of the insulating paper using the DP-value is currently not possible during operation, as a paper sample is

Table 1. Direct and indirect methods for determination of DP-values

Parameter	Method	Pro	Contra
Direct measurement of the cellulose chain			
DP-value	Viscometric according to IEC 60540	Precise and standardized	N/a for transformers in operation
Indirect methods by detection of degradation products in oil			
CO and CO_2	Gas chromatograpy	Standard online method with DGA	Interference by oxidation of oil and environment
Furanic compounds	Liquid chromatography according to IEC 61198	Offline oil analysis, widely used in field, indication of insulation aging	Offline, cannot deliver exact DP-values, wrong conclusions for different oils
Ethanol / methanol	Chemical analysis	Potential for online method with DGA	Method still under development

necessary for this purpose. The removal would demand significantly high efforts and costs. A sampling of the insulating paper is only possible during maintenance or decommissioning of the transformer. State of the art of direct measurement of DP-values for cellulose is a viscometric determination according to IEC 60540 in certified laboratories.

An indirect condition monitoring refers to a quantitative investigation of substances in the insulating oil, which are produced by cellulose decomposition processes and accumulated in the surrounding liquid. These markers affect the physicochemical parameters of the insulating liquid [7].

For example, the aging of the paper in mineral oil produces furans, and by measuring the furan content according to IEC 61198, information about the aging condition can be obtained [8-10]. An advantage of the indirect method is a non-destructive measurement during the normal operation in the field because of the possibility to take insulating oil samples from a transformer without great effort. However, limited accuracy is obtained due to the indirect method via degradation processes. Analyzing furanic compounds requires an offline effort of sampling and measurements [11]. However, the limited repetition rate of the manual sampling makes permanent condition monitoring impossible.

Furthermore, recent studies at the Schering-Institute [12] show diverging results for different oil types. Fig. 2 shows the concentration of the furanic component 2-FAL during aging of oil-paper insulation experiments vs. aging time. The concentration of 2-FAL in uninhibited oil shows a rapid initial increase of 2-FAL concentration followed by a steady decrease for an aging time exceeding 400 h. The decrease might be related to the decomposition of 2-FAL or diffusion out of the oil or possible migration back into the insulation paper. Such interactions make a one-to-one correspondence of 2-FAL or other furanic contents to DP-value more than questionable.

Concentrations of 2-FAL in Fig. 2 in inhibited oils and synthetic oils show at least increasing content over the aging time but different for both inhibited oils. Also, it could be demonstrated that there is a remarkable influence of furanic content in the oil in respect to paper arrangements in the transformer and type of preservation construction (open or hermetic transformers). It has been concluded that the increase of furanic components is an exclusive indication of thermal aging of the paper, but it cannot exactly deliver the DP-value [12]. The accuracy of the furanic analysis is limited and depends strongly on the type of oil. The published algorithms for uninhibited oils cannot be used for newer oils without leading to a significant inaccuracy.

CO and CO_2 are also produced in the degradation process of cellulose, and such molecules can be measured online, utilizing available DGA oil analysis techniques. Also, for this methodology, limited accuracy in DP-value determination is obtained due to possible interferences with chemical processes in the oil and between the oil and environment.

Ethanol and methanol might also be produced during the degradation of cellulose, but these methods are still under development and not widespread so far, leading to an insufficient experience in the interpretation of ethanol and methanol contents.

Table 1 shows a summary of the established direct and indirect methods for determining DP-value and their specific advantages (pro) and disadvantages (contra).

The basis for the optical methodology is the empirical observation that insulation papers show changes in optical parameters during the aging process

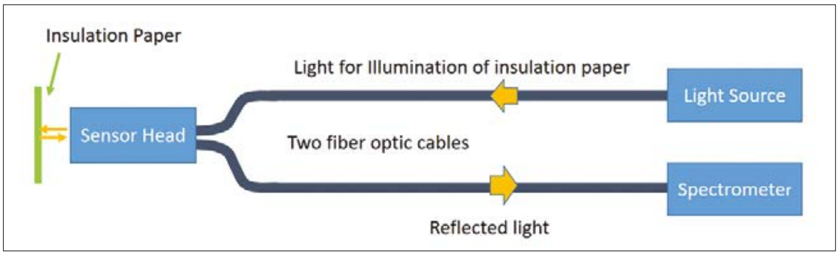

Figure 3. Principle of optical reflection spectroscopy of insulation paper

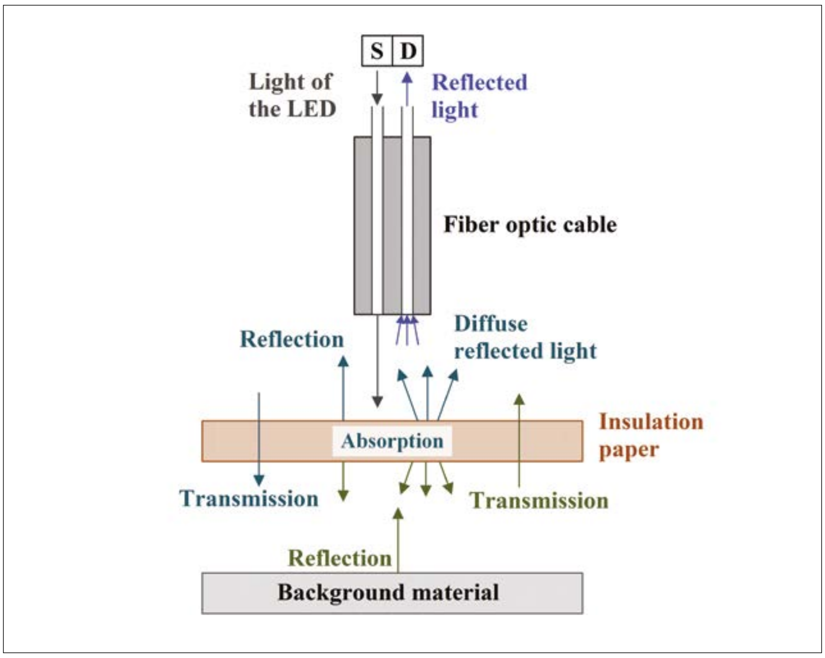

Figure 4. Schematic setup of the sensor head and path of light during the measurement

Figure 5. Arrangement of oil-paper samples during thermally accelerated ageing in the oven

To find a correlation between the optical reflection spectrum and the degree of polymerization of insulation paper, an experimental investigation has been conducted

Besides focusing on transformer diagnostics, the subject of our current research and product development is the development of a cost-effective and efficient direct, and precise online method for determining the condition of the insulating paper without the need for disconnection from the power grid. Typical kraft papers have been aged in different insulating fluids, which are commonly used in transformers, and a correlation between the reflection spectrum and the DP-value has been investigated [13, 14].

Based on the research results, product development has been initiated for precise online monitoring of the polymerization degree of insulation papers inside power transformers.

3. Optical methodology

The basis for the optical methodology is the empirical observation that insulation papers show changes in optical parameters during the aging process. Therefore, an optical system was developed using principles of optical spectroscopy, shown in Fig. 3.

The insulation paper is illuminated at the sensor head with a light source via a fiber optic cable, and reflected light is collected by another fiber optic cable and transferred to an optical spectrometer. As seen in some more details in Fig. 4, processes of absorption, reflection, and transmission occur in insulation paper, and diffusely reflected light is collected by optical fiber into the spectrometer.

4. Scientific methodology

In order to find a correlation between the optical reflection spectrum and the degree of polymerization of insulation paper, a method for defined aging and characterization of accurate DP-value has been established.

As already mentioned, with the IEC 60540, there is a well-established method of viscometric determination of polymerization degree. By aging insulation papers in different transformer oils and other fluids like natural or synthetic esters, samples with different aging status have been created. The degree of polymerization has been measured according to IEC 60540 and set into correlation with the optical parameters from reflection spectroscopy resulting in a sensor value via mathematical algorithms, e.g., least-square fit procedures.

5. Aging of the oil-paper insulation

In this investigation, 11 different paper sample sets were used for the spectral analysis. These paper samples aged in different types of insulating liquids and systems, intended to simulate various operating modes, designs, and exploitation of a transformer. The simulation of a freely breathing transformer with an oxygen and moisture input from the ambient air is called an open system in this work, whereas a closed system means a hermetically sealed transformer. In addition, a distinction is made between heterogeneous and homogeneous aging, as shown in Fig. 5. Heterogeneous aging means that the paper strips remain layered in the insulating oil. In contrast, homogeneous aging refers to the uniform aging of the individual paper strips. This is achieved by arranging the paper strips next to each other, ensuring uniform contact with the insulating oil, to investigate if the arrangement of the paper has an influence on the measurement with the sensor.

With the aid of a large number of paper samples, it has been investigated whether the sensor value would change due to different influencing factors of various insulating liquids. The examined paper samples have been aged in a non-inhibited mineral Oil A, an inhibited mineral Oil B, and another inhibited Oil C with a different composition. Oil A and Oil B are classic mineral oils, while Oil C is a synthetic oil. Paper samples aged in the ester liquids Ester A, Ester B, and Ester C were also tested. The liquids Ester B and Ester C are natural esters, while Ester A is a synthetic ester.

It is worth mentioning that in this study, the insulating paper *Grade K Insulation Paper* of the company *Weidmann* was used. This is a light calendered paper with a thickness of 0.1 mm and a density of 0.75 – 0.85 g/cm^3 [15].

For homogeneous accelerated aging, paper strips with a total mass of 100 g were hung in a 10 l stainless steel container. Therefore, the insulating papers were

> **A correlation between the sensor-value and the DP-value has been found for all different aging systems and insulating fluids**

hung up on a line and immersed in oil, as shown in Fig. 5.

Prior to the aging process, both the paper strips and the insulating liquid were dried, whereby the insulating oil was degassed in addition to a drying process. Drying and degassing are carried out to reduce the oxygen and moisture content, thus preventing premature catalysis of the decomposition processes [16]. The paper strips were dried for 48 hours at 80 °C under vacuum, while the drying and degassing of the insulating oil was carried out in an oil treatment system. The system uses a vacuum pump to reduce the pressure to a value of 0.5 mbar, and at the same time, the temperature was raised to 65 °C with the aid of a heating circuit, allowing any gases and moisture present in the oil to evaporate. After the dried paper samples were impregnated with the processed insulating fluid in a vacuum chamber at 80 °C, the paper samples were aged in a heating cabinet with air circulation at a temperature of 130 °C. Copper tubes, 15 cm long and 65 g heavy, with a wall thickness of 1 mm and a surface area of 320 cm², were added as a catalyst to the paper samples in order to simulate the paper aging as realistically as possible. The stainless-steel containers were covered with a lid to minimize the oxygen and moisture ingress. In total, the paper samples were aged for 3192 hours (19 weeks) with Oil C.

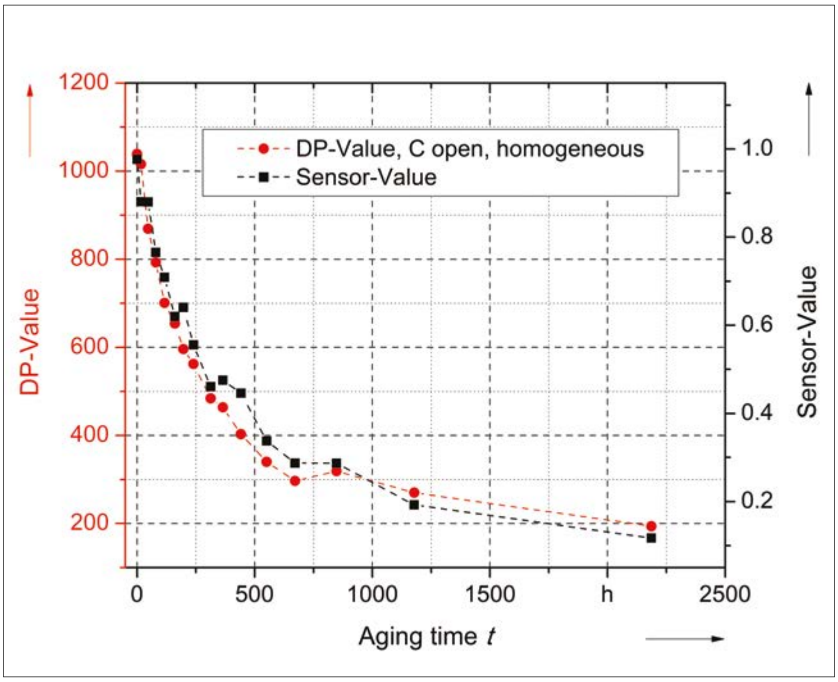

Figure 6. Measured DP-value (red) via viscometry and measured sensor value (black) over aging time for Oil C in an open system with a homogeneous arrangement

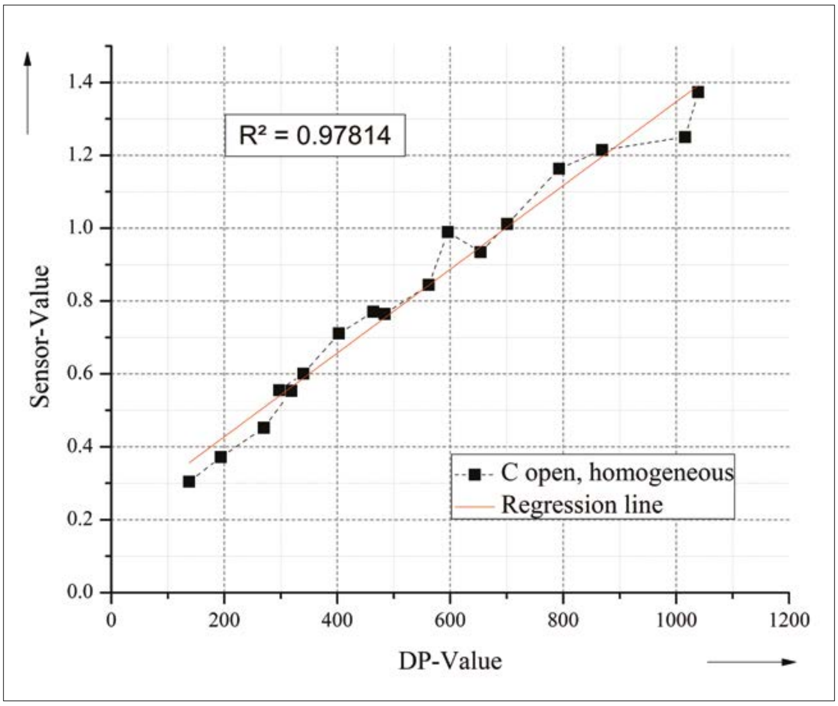

Figure 7. Linear correlation between the sensor-value and the DP-value for Oil C in an open system with a homogeneous arrangement

The heterogeneous open aging method was intended to replicate the decomposition process of insulating paper in a free-breathing transformer with Oil A, B, and C. In contrast to the previous section, the impregnated insulating papers were not sorted and hung in an elongated stainless-steel container but placed in Erlenmeyer flasks in an overlaying order. For the aging process, a total of 30 Erlenmeyer flasks were filled with 160 g paper and 1600 g insulating oil each, which corresponds to a typical weight ratio (1:10) of paper to oil in a transformer [17]. In addition, a copper pipe was added to the paper, for the reasons already mentioned. The drying and degassing were carried out in advance, as well as the sampling and extraction of the insulating oil, same as before. In total, paper samples for three different oils were aged according to this aging procedure for a period of 15 weeks. The paper samples and the corresponding insulating oil were taken at weekly intervals in the beginning, with the first sample being taken before the aging process initiation. The remaining samples, including the insulating fluid, were taken at two-week intervals and at the end in a three-week interval.

The heterogeneous closed aging process is analogous to the heterogeneous open one

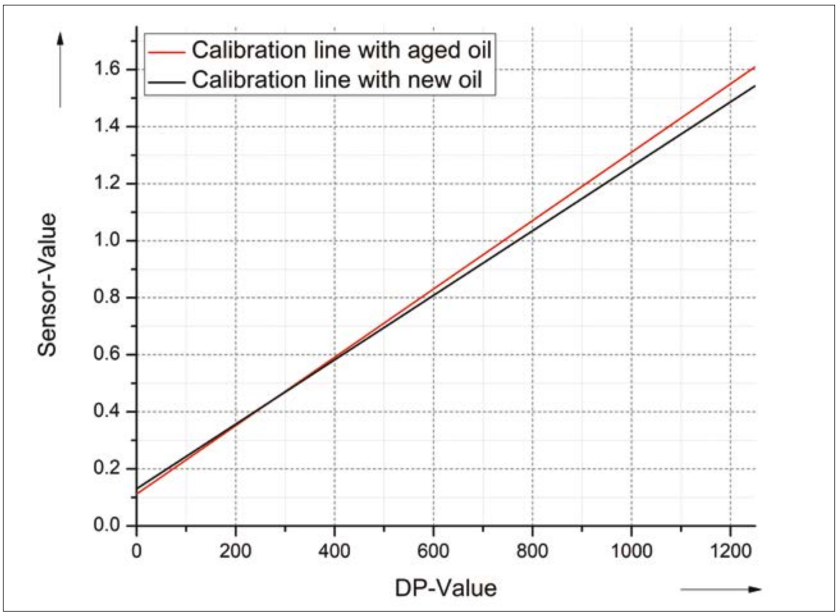

Figure 8. Calibration lines recorded under aged and new oil.

with Oil A, B, and C as well as Ester A, B, and C. The only difference in this context is the airtight closure of the Erlenmeyer flasks by a silicone rubber plug. The aging process of these samples is the same as described for the open system. The papers were placed heterogeneously in an Erlenmeyer flask and aged in a heating cabinet at 130 °C for 2016 h.

In addition, the aging of pure non-impregnated paper samples was carried out in the air, whereby the aging was also thermally accelerated at 130 °C within a heating cabinet.

6. Results

Aging analyses of all combinations of oils and fluids, insulation papers, and transformer configurations have been performed. Fig. 6 shows an example of the aging process of Oil C in an open configuration and homogeneous treatment. DP and sensor values in the figure already indicate corresponding behavior.

A careful analysis of the correlation of the measured sensor-value derived from the reflection spectra of the different paper samples with the DP-value determined according to IEC 60450, using the viscometric method, has been investigated for all combinations of different oils and synthetic and natural esters as well as open or closed systems and homogenous and heterogeneous arrangements.

A correlation between the sensor-value and the DP-value has been found for all different aging systems and insulating fluids, which allows for an easy determination of the DP-value. As an example, Fig. 7 shows a correlation between sensor-value and DP-value for open system aged in Oil C.

It turned out that the correlation of all combinations of fluids and aging conditions showed very similar behavior.

Fig. 8 shows the calibration lines determined by averaging the regression lines from all measurements. The measurements were also carried out using fresh new oil to determine whether the insulating fluid has an effect on the determination of the sensor-value. As can be seen, both calibration lines are almost identical, so it can be assumed that the insulating liquid surrounding the paper has no influence on the determination of the sensor-value.

To assess the reliability of the calibration model, average absolute prediction errors ΔDP were calculated as shown in Equation (1). For this purpose, differences of the individual laboratory DP-values $DP_{i,Lab}$ and the DP-values $DP_{i,Sensor}$ predicted with the calibration line were calculated.

Table 2. Distribution of the prediction errors for different DP-value ranges

DP-value range	DP ≤ 300	300 < DP ≤ 500		500 < DP ≤ 800	800 < DP
Deviation	17	91		71	74

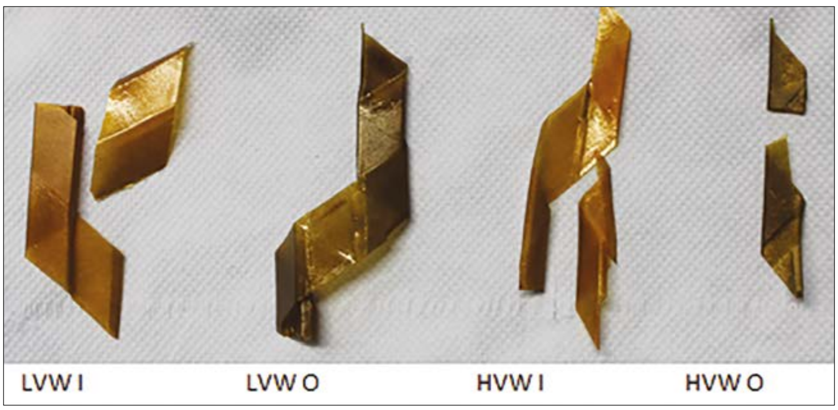

Figure 9. Paper samples of a real transformer, which was in operation for more than 50 years.

Based on the experience with this reliable optical technology, product development on insulation paper sensing has been launched

$$\Delta DP\ Ratio = \frac{\sum_{i=1}^{n} |DP_{i,Lab} - DP_{i,Sensor}|}{n} \qquad (1)$$

Table 2 shows average absolute deviations of the predicted DP-values from the laboratory values.

It is shown that an accuracy of at least 91 DP-points is achieved over the entire lifetime. In addition, accuracy of at least 17 DP-points is obtained, especially in the important area of the end of life around DP of 200.

For further investigation regarding the prediction of the DP-value by means of the sensor, a real transformer paper was examined. The paper comes from a transformer that has been in operation for more than 50 years, shown in Fig. 9. There are samples from both the high voltage (HVW) and low voltage windings (LVW), as well as the outer (O) and inner (I) layers.

Table 3. Determination of the DP-value using IEC 60450 and the sensor

Sample description	IEC 60450 DP-value	Predicted DP-value
HVW O	211	260
HVW I	195	211
LVW O	193	156
LVW I	196	131

The deviation between the measured and calibrated value is within the range of 2-6 %, and the standard deviation is around 6-8 % of the calibrated value, which shows the potential for high accuracy of this technology

The DP-values determined in the laboratory according to IEC 60450 and the DP-values determined by the new sensor are shown in Table 3. On the one hand, it can be seen that the values correspond very well with each other. Furthermore, it can be observed that the values determined in the laboratory are all close to 200. However, it seems that the values which have been determined by the sensor correspond better with the theory of aging; thus, lower DP-values are expected on the low voltage side due to higher temperatures. Furthermore, the sensor values show lower values at the inner layers than at the outer layers, which is reasonable but cannot be detected by the chemical DP-analysis because this method seems to be too inaccurate for detecting small differences. Therefore, it has to be concluded that the sensor system delivers more

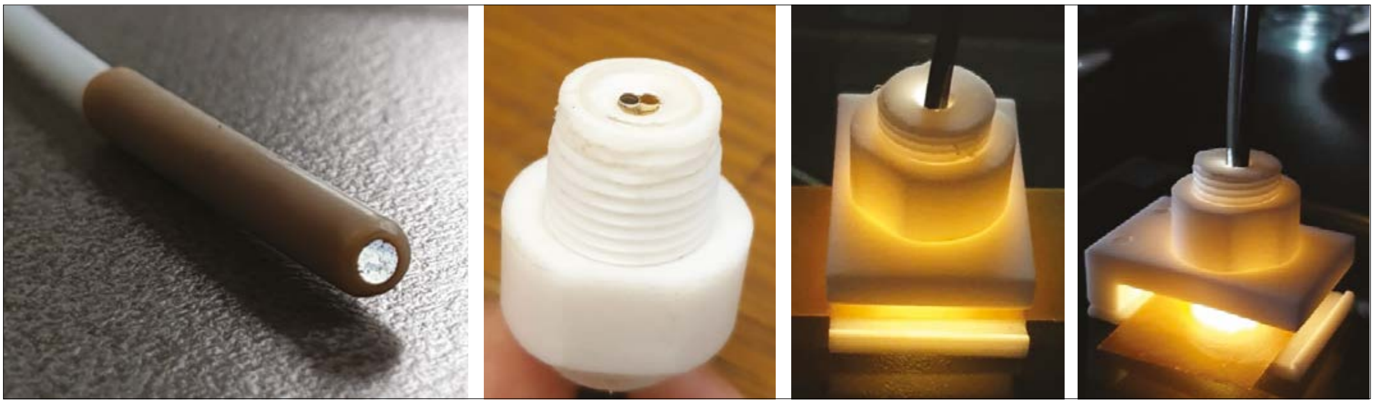

Figure 10. Sensor heads for use in transformer (two left), two right: with a holder for insulation paper

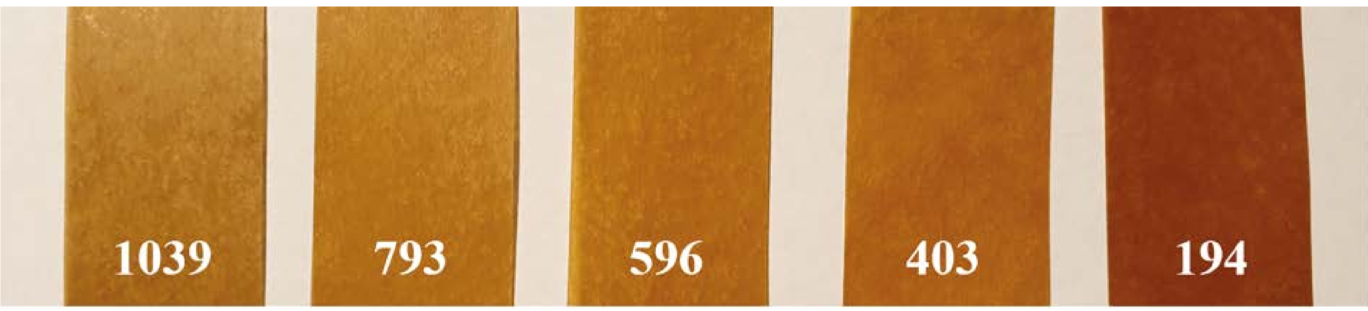

Figure 11. Aged insulation papers calibrated for DP between 1039 and 194 by viscometric analysis according to IEC 60540 (calibrated DP-values shown in the figure)

A sensor head and fiber optic cable tests are currently performed on the transformer in operation, and the first results indicate thermal stability up to 130 °C

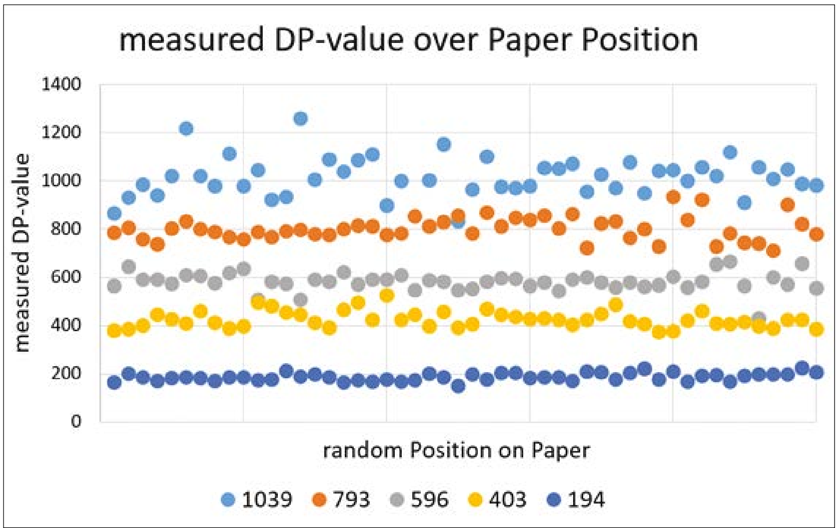

Figure 12. Test results on 50 randomized positions on different aged and calibrated insulation papers.

Table 4: Deviation analysis

DP-value calibrated	194	403	596	793	1039
DP-value mean	189	428	583	804	1018
Deviation DP-value	-5	25	-13	11	-21
Standard deviation	16	34	39	49	81
% deviation	-2.6 %	6.2 %	-2.1 %	1.3 %	-2.0 %
% standard deviation	8. 5%	8.0 %	6.6 %	6.1 %	7.9 %

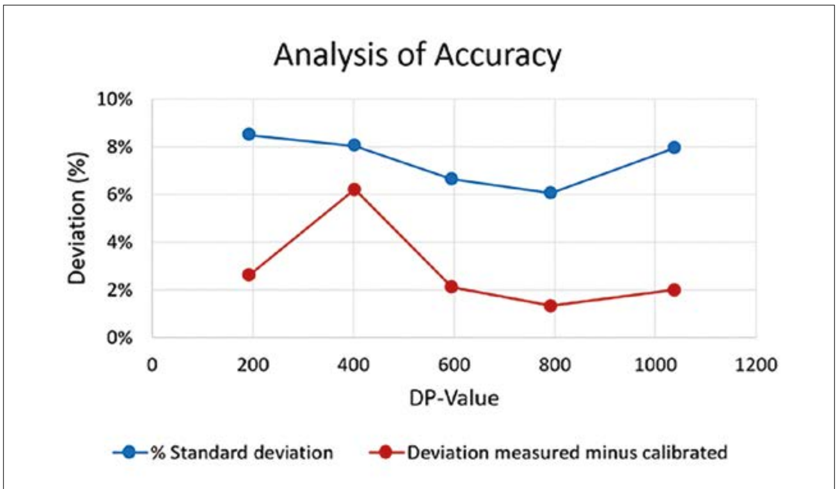

Figure 13. Deviation analysis of DP-value measurement: percentage of the standard deviation of 50 test points and deviation between measured and calibrated value

reliable and precise values than the method according to IEC 60450.

7. Sensor head for online monitoring inside transformers

Monitoring the quality of insulation paper at the winding hot spot of a transformer requires technology with stable performance over the entire lifetime of a transformer, e.g., for a period of 50 and more years. The following requirements need to be fulfilled by the sensor technology:

- long time stability and accuracy of the signal,
- chemical compatibility in respect to all transformer fluids,
- thermal compatibility and stability up to hot spot winding temperature and in respect to dynamic thermal cycles,
- stability in respect to mechanical transformer environment with permanent vibration,
- stability in respect to the electromagnetic transformer environment.

Optical fiber technology in transformer monitoring has been well established in the field of online temperature measurements over the last decades and is now state of the art in reliable hotspot winding and top oil temperature monitoring.

Based on the experience with this reliable optical technology, product development on insulation paper sensing has been launched, and appropriate optical fiber and sensor head materials have been selected for functional prototypes of a new DP-value sensor to ensure permanent high electrical insulation and chemical, mechanical, electromagnetic and thermal compatibility to the transformer environment. Fig. 10 shows functional prototypes of different sensor heads based on optical fiber technology for the use inside a transformer and a sensor mounted on a holder for insulation paper.

For functional testing of transformer use prototypes, aged insulation papers measured by viscometric analysis according to IEC 60540 DP-values from 1039 to 194 have been selected to represent the entire range of values during the lifetime. Fig. 11 shows calibrated paper samples and an indication of DP-values.

Each calibrated insulation paper has been measured at 50 randomly selected positions on one side of the paper by the prototype sensor. The test results are shown in Fig. 12. The measured DP-values of different papers can be easily distinguished from each other. Fig. 13 and Table 4 show a deviation analysis of the measurements. The deviation between the measured and calibrated value is within the range of 2-6 %, and the standard deviation is around 6-8 % of the calibrated value, which shows the potential for high accuracy of this technology.

It should be noted that the deviation analysis shows the highest accuracy of approximately 20 DP in the region of 200 DP, are demonstrating the potential for a precise sensor methodology for determining the end-of-life of transformers.

Repeated measurements at one spot of the paper without moving the sensor head show very high repeatability with standard deviations below 1 %, indicating that standard deviations on the paper shown in Fig. 12 and Table 4 are due to spatial inhomogeneity over the insulation paper.

8. Tests under transformer conditions

Transformer conditions at hot spot winding require a temperature range up to 130 °C and more in oil and ester fluid environments. Therefore, a sensor head and fiber optic cable tests are currently performed. The first results indicate thermal stability in the given temperature range. Long time tests are prepared for different oils and esters and also inside real transformers for pilot testing.

Fig. 14 shows a sensor head for monitoring DP-value mounted on a lead inside a transformer.

Figure 14. Sensor head for monitoring insulation paper mounted on a lead inside the transformer

9. Discussion

The methodology for measuring DP-values using optical reflection spectroscopy inside transformers is an innovative and promising technology with an opportunity for a much more precise online transformer lifetime management.

Laboratory tests of the optical method show consistent results for DP-value with different kinds of aging fluids (mineral oils and esters), old and new oils, even with papers aged in the air. The results are in general agreement with previous studies using similar methodology from a group from the University of Surrey [18].

Tests of the methodology in respect to repeatability and reproducibility indicate high accuracy of the new optical method, and there is a clear correlation found between the measurements with an optical sensor and viscometric tests for DP-value determination according to IEC 60540.

Since the calibration of the optical sensor is based on the correlation with viscometric tests, uncertainties in the viscometric test results influence the calibration of the optical sensor. In fact, some deviation is found in the viscometric test results as well. Therefore, differences between optical and viscometry measured DP-values are also related to deviations in the viscometric measurement.

Potentially, the optical method might have higher accuracy in respect to the viscometric methodology, which makes the optical

An online monitoring system with the condition assessment of transformers paper insulation would be feasible using proposed optical sensors, which is not currently available on the market

method also attractive for laboratory use, besides the much faster and non-destructive character of the methodology. Laboratory devices could be designed quite compact and handheld, enabling in-situ tests on-site, e.g., at transformer assembly or recommissioning lines or even in the field.

In addition, high speed of data acquisition and accuracy opens up an opportunity for the optical methodology for online monitoring of polymerization degree in industrial paper production lines for quality and production control.

For viscometric measurements, insulation paper is chemically solved, and the average DP-value is determined for the whole paper. With the optical measurement, a light spot on the paper is illuminated and measured for the DP-value determination. As mentioned above, the spatial fluctuations over the insulating paper shown in Fig. 12 might at least be partly related to the spatial inhomogeneity of the paper. By averaging different spots on the paper or by increasing the measured spot area, an average DP-value can be determined by the optical method as well.

The new DP-value sensor technology is based on the same fiber optic technology so that the new technology can be implemented as a new standard, potentially in a much shorter time frame, by using similar materials for sensor head and fibers. Therefore, laboratory and validation tests inside transformers have to be performed and completed for market acceptance and to prove the reliability of the new technology.

10. Conclusion

In this work, a patented sensor technology that allows a reliable determination of the DP-value by means of an optical method has been scrutinized. With this method, an online monitoring system with the condition assessment of transformers paper insulation would be feasible, which is not currently available on the market. The measurement is carried out non-destructively within seconds, resulting in considerable advantages over the destructive viscometric method according to IEC 60450. The time-consuming sampling of paper is therefore no longer necessary. The tests were carried out using accelerated aged paper samples in the laboratory, aged in air and different insulating liquids, simulating various systems (free-breathing and hermetically sealed transformers). It could be shown that monitoring under the measurement environment of a transformer is possible and that this can be done independently of the type of insulating liquid. There is clearly a correlation between the sensor-value and the DP-value, which allows a simple and reliable determination of the aging condition of the paper. In addition to online monitoring of insulation paper in transformers, it is possible to use the sensor technology for analyses in laboratories, which allows for a simplified and faster measurement of the paper condition. Product development of functional sensors for online monitoring in transformers and for laboratory devices for different paper samples are currently under development.

Authors

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Prof. Dr.-Ing. **Peter Werle** studied electrical engineering at the University of Hannover and did his PhD afterward at the Schering-Institute in Hannover. From 2003 to 2014, he was with ABB Transformer Service in different national and international positions. From 2010 to 2014, he was the general manager of the Transformer Service in Germany and responsible for the workshops in Halle (Saale), Neusäss (close to Augsburg), and Nauen (close to Berlin) with over 200 employees. Since October 2014, he is the head and director of the Schering-Institute for High Voltage Engineering and Asset Management of the Leibniz University in Hannover. He is a Member of the VDE, DKE K 182, IEEE, and CIGRÉ and active in CIGRÉ as liaison officer between A2 and IEC TC 10 and between A2 and CIRED, as well as head of the Advisory Group AG A2.8 and member of the A2 strategy board. Furthermore, he is active in various working groups of CIGRÉ and IEC TC 10. He is the inventor of more than 20 patents and is the author or co-author or more than 350 publications in the area of high voltage testing, partial discharge diagnosis, condition monitoring, and asset management.

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