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Internationales Wissenschaftliches Kolloquium
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Information Technology and Electrical Engineering - Devices and Systems, Materials and Technologies for the Future

Faculty of Electrical Engineering and Information Technology

Startseite / Index:
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TECHNISCHE UNIVERSITÄT
ILMENAU

Impressum

Herausgeber:	Der Rektor der Technischen Universität Ilmenau Univ.-Prof. Dr. rer. nat. habil. Dr. h. c. Prof. h. c. Peter Scharff
Redaktion:	Referat Marketing Andrea Schneider Fakultät für Elektrotechnik und Informationstechnik Univ.-Prof. Dr.-Ing. Frank Berger
Redaktionsschluss:	17. August 2009

Technische Realisierung (USB-Flash-Ausgabe):
Institut für Medientechnik an der TU Ilmenau
Dipl.-Ing. Christian Weigel
Dipl.-Ing. Helge Drumm

Technische Realisierung (Online-Ausgabe):
Universitätsbibliothek Ilmenau
ilmedia
Postfach 10 05 65
98684 Ilmenau

Verlag:
isle
Verlag ISLE, Betriebsstätte des ISLE e.V.
Werner-von-Siemens-Str. 16
98693 Ilmenau

ISBN (USB-Flash-Ausgabe): 978-3-938843-45-1
ISBN (Druckausgabe der Kurzfassungen): 978-3-938843-44-4

Startseite / Index:
http://www.db-thueringen.de/servlets/DocumentServlet?id=14089

ON-LINE MONITORING OF CAPACITANCE AND DISSIPATION FACTOR RELATED TO AGEING RESEARCH RESULTS ON OIP

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ABSTRACT

Bushings are exposed to high thermal and electrical stresses, and monitoring becomes more and more important. A new solution for on-line monitoring of capacitance C and dissipation factor tan δ at power frequency, service voltage and service temperature is presented. Excellent accuracy is achieved. Increasing dissipation factors and simulated partial breakdowns were clearly detected. For a monitoring, it is important to understand mechanisms and parameters of oil impregnated paper (OIP) ageing. Ageing investigations were performed on 36 OIP bushing insulation models. Parameters were air vs. nitrogen gas volume, with vs. without electrical field stress and different temperatures (80, 90 and 105 °C). The results show the effects of temperature and access of air. Also an influence of the electrical field can clearly be recognized. Ageing of OIP can be detected from on-line dissipation factor measurements at service temperature, but not at ambient temperature.

Index Terms - PDC, insulation, dissipation factor, conductivity, OIP, On-line, monitoring, ageing

1. INTRODUCTION

Bushings are strategically important components for plants and substations. They are the “bottle necks” of energy transport and they are often exposed to high permanent stresses. Normally, there is no significant ageing, even for oil impregnated paper (OIP) cores at high service temperatures [1].

Nevertheless, sometimes there are sudden unexpected increases of dissipation factor, which might be critical. Up to 30 % of power transformers failures are attributed to the bushings [2], [3]. Therefore, evaluation and monitoring of OIP bushing insulation condition is very important.

Dielectric field diagnosis of bushings is normally performed by off-line power frequency measurements of capacitance C and dissipation factor tan δ at the measuring or potential tap which is connected to the outermost or second grading foil.

The bushing capacitance is a sensitive quantity for the detection of partial breakdowns between grading foils. Unfortunately capacitance does not give information about the ageing condition, neither in off-line nor in on-line measurements, but it is a good emergency indicator within an on-line monitoring system. During off-line measurements, when dissipation factors tan δ are measured at ambient or room temperature, the values are low and rather insignificant, even for a strongly aged or wetted insulation, Fig 1 (left).

The dissipation factors at real service temperatures above 50 °C remain unknown, although they might be high and dangerous. At service temperature high dissipation factors can indicate ageing and the danger of thermal instabilities, Fig. 1 (right). For severely aged OIP insulation thermal instabilities might occur even at elevated service temperatures. Therefore it is desirable to measure the tan δ on-line at service temperatures by using an on-line monitoring system [4].

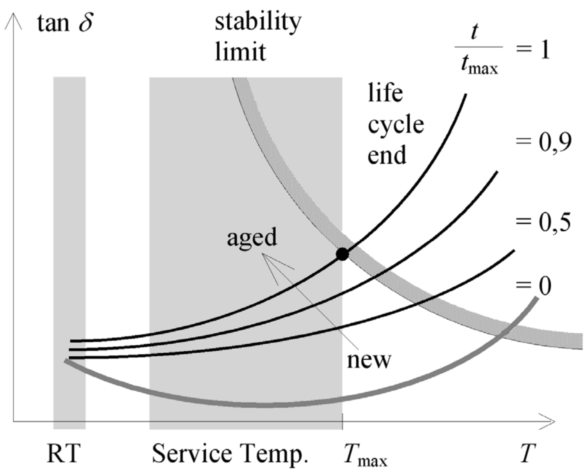

Figure 1: Degradation of thermal stability by ageing of the OIP insulation [4] (schematical).

2. ON-LINE MONITORING MEASUREMENTS

Existing bushing monitoring systems make use of basic quantities such as oil-level, pressure and temperatures in order to detect dangerous conditions and to prevent thermal runaways [3]. Also capacitance is proposed for the detection of partial breakdowns [6], [7]. The dissipation factor is not yet commonly used, although it has a high potential to detect the slow progress of ageing, and to identify critical situations far prior to thermal problems and to a total breakdown. Interest is concentrated both on changes of the main insulation capacitance *C* giving a direct emergency indication of partial breakdowns and on changes of the dissipation factor tan δ giving permanent information about the ageing condition and the possible danger of thermal instabilities. *C* and tan δ under service conditions are key quantities of advanced on-line bushing diagnosis systems.

2.1. Determination of *C* and tan δ

Capacitance and dissipation factor can be determined by current signals taken from the measuring or potential tap of the bushing. These signals have to be compared with signals provided by a reference path.

Originally, it was proposed to compare insulation characteristics of three bushings among each other within a three-phase system [2], [7]. Reference signals are generated by summation of the signals of the three bushing signal currents or by an analogous resistive summation. If the measured currents from the three bushing taps are perfectly balanced the sum is zero. If the dissipation factor increases, e.g. in the bushing of phase A, the active current through bushing A rises. The vector sum is an additional current. It indicates a change of tan δ in one of the bushings. But this principle does not work if the insulation of three bushings ages simultaneously. A change of a bushing capacitance can also be detected by amplitude changes, but fluctuations of phase voltages and phase angles in service cause significant inaccuracies. This kind of on-line monitoring systems already exists and is used in service [2], but single-phase transformer can not be supervised with such a system.

2.2. New approach for monitoring of *C* and tan δ

Up to now the measurement of *C* and tan δ for a single bushing is possible as an off-line measurement at ambient temperature only. There are two disadvantages: Subsequent measurements are taken in very long time intervals which are definitely too long for the detection of a progressive failure development. Furthermore it is not possible to evaluate the dissipation factor tan δ at service temperature from a given measurement at room temperature, Fig. 1.

Therefore permanent supervision resp. the on-line monitoring of capacitance *C* and dissipation factor tan δ at real service temperature is most desirable. These quantities contain valuable information. Partial breakdowns, which require immediate action, can be seen from changes of capacitance. The dissipation factor tan δ at service temperature is a direct measure for dielectric heat production, which might be a danger for the thermal stability of the insulation [4].

Traditionally, *C* and tan δ are measured in special bridge circuits (e.g. Schering bridge), containing the bushing to be measured and a reference capacitor with well-known and stable properties. Manual or automatic balancing of the bridge provides very accurate results, but a bridge is too complex for an on-line measuring system. So the choice has made to get the needed information resp. signals for the monitoring system from the bushing's tap and from a reference path. Then both signals get digitized and compared continuously.

2.3. Reference Signal and Signal Processing

The needed reference signal could be taken out by use of the stray and air capacitances, Fig. 2. The use of stray capacitances is common practice for measuring of fields and voltages, e.g. for electrostatic voltmeters or capacitive probes [8].

The signals, which shall be compared, are fed into a microcontroller through an A/D-converter and are further processed digitally. In this step it is important to process the digital input data by means of advanced signal theory algorithms for correct phase difference measurements, in order to exclude harmonics and in order to be able to process the pure and undisturbed power frequency signal afterwards. In the further analysis the phase difference is determined digitally and treated with advanced mathematical operations. Due to the availability of digital data, discrete fast Fourier transformation (FFT) algorithms can be used to transform signals from the time to the frequency domain. In the frequency domain the amplitudes of harmonics can be determined. In order to arrange this complex system as user-friendly as possible, a clear layout was developed, which provides the most important quantities in graphs and/or tables.

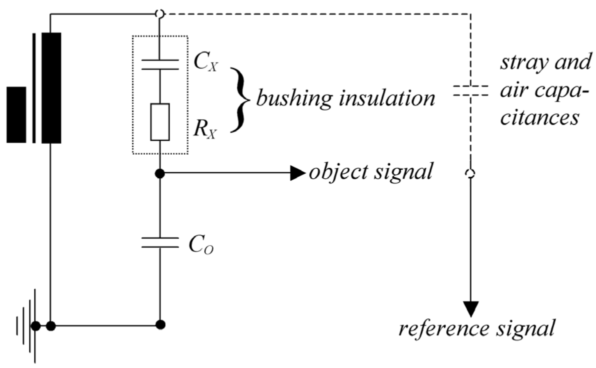

Figure 2: Circuit for dissipation factor measurements by use of stray and air capacitances.

In addition to this new system experimental investigations on the ageing process of oil impregnated paper (OIP) have been performed, chapter 4. With these investigations a better understanding of the ageing process of OIP bushings should be achieved, and relationships between the monitored quantities and the insulation history and insulation condition should be established. This was necessary because the research of the ageing process of OIP insulation in the past was concentrated on the main application of OIP - the insulation in transformers itself.

3. RESULTS

3.1. Detection of increasing dissipation factors

The described monitoring system was tested with oil impregnated paper (OIP) samples with high water content. It behaves similar to an aged insulation. The reference signal was taken from a potential free toroid, which was coupled to the high voltage side by stray capacitances [9]. In order to examine the function of the system, the measured dissipation factor tan δ was compared with the results from a Schering bridge measurement. For the sensitivity estimation of the system the temperature of the sample was increased to a typical service temperature within the core of a bushing. Thereby the dissipation factor of the wet OIP sample increased dramatically due to the poor insulation quality.

Already the first results from the on-line monitoring system were in good agreement with the off-line Schering bridge measurements. Several steps of signal processing improvements could be achieved, e.g. by advanced statistical analysis of digital data with improved mathematical operations, Fig. 3.

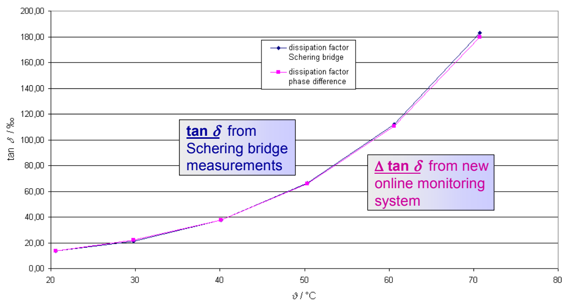

Figure 3: On-line dissipation factor monitoring in comparison to Schering-bridge measurements.

The comparison with an accurate Schering bridge showed that the absolute accuracy of the determination of dissipation factor changes was close to 0.001. Dangerously increasing dielectric losses of wet or aged OIP-samples at service temperatures can clearly be detected. Like in this example of a significantly wetted OIP sample, the monitored dissipation factor values would mean a high danger of a thermal instability in case of a real bushing, but however it would have been clearly recognized by the described on-line monitoring system, already in an early stage of ageing.

3.2. Detection of partial breakdowns

Furthermore the system was tested in order to detect a change in capacitance as it would happen during a partial breakdown. For this purpose an original 110 kV bushing (C = 230 pF) with an additional capacitor (C_{sim} = 21 nF) in series was used. The series capacitor could be bypassed by a switch, to simulate a change in the system capacitance of approx. 1 %, Fig 4. This is similar to the change of capacitance during a partial breakdown between two grading layers in a big bushing.

Figure 4: Test setup to simulate a partial breakdown by short circuit of a series capacitance.

The result of the measurement can be seen in Fig. 5. The values of the capacitance change directly by approx. 1 % when the switch gets opened or closed. The switch starts open before it gets closed and opens again. This process of “self-healing” is not possible with a bushing, it just demonstrates the performance of the monitoring system. The first three hours of the increasing tan δ values must not be considered here, they are caused by the warming up of the system.

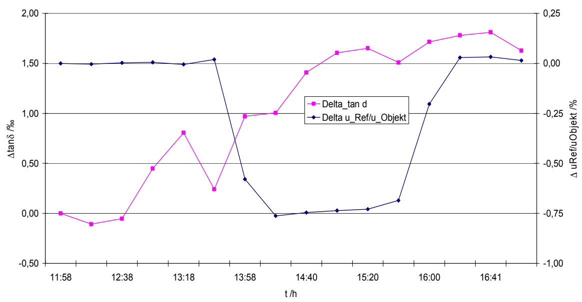

Figure 5: Detection of capacitance changes.

4. AGEING INVESTIGATIONS

For a better understanding and interpretation of the monitoring system results, ageing investigations were performed on bushing models which should have ageing conditions comparable to real bushings in the grid. Therefore the models were designed with the original bushing materials. The influence of electrical field strength, the influence of air access and the influence of different ageing temperatures were investigated.

For dielectric diagnosis dissipation factor (tan δ) measurements and polarization/depolarization current (PDC) measurements at different temperatures were planed. Additionally partial discharge (PD) measurements could be done in case of interest.

Figure 6: Prototype of a bushing model for the ageing investigations under different conditions.

For this purpose bushing models have been built, Fig. 6. Ageing was performed with different conditions, Fig. 7. For an accelerated ageing the bushing models were aged at high temperatures. As a parameter for the ageing process the access of air/humidity vs. a hermetic enclosure with nitrogen gas has been investigated. Additional parameters were different temperatures and the presence or absence of electrical field strength, Fig. 7.

With the ageing results of these bushing models a better understanding of the monitoring system results should be achieved.

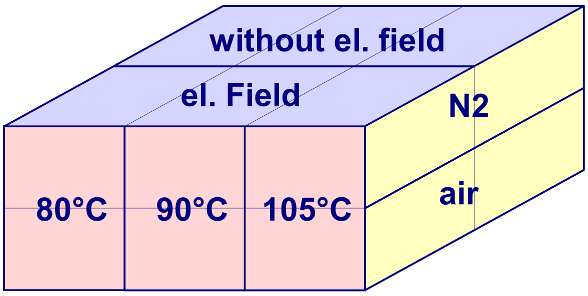

Figure 7: Parameters for the accelerated ageing investigations on bushing models.

4.1. Measurements and results

Dissipation factor measurements are strongly dependent on temperature. Therefore a comparison of the different ageing models could only be done at the same measuring temperatures. For this purpose the electric ovens regularly are set to 90 °C and sometimes to room temperature.

In order to allow a comparison of the 12 parameter combinations, the following procedure is done: At 90 °C the changes of the dissipation factors tan δ in comparison to the initial measurement at this temperature are determined. The values in each parameter group are averaged, Table 1. This average is seen as the characteristic value for this group and is compared to the values of the other 11 parameter groups.

Table 1: Example for the determination of the characteristic dissipation factor change at 90 °C (Group N_105_E0: Ageing temperature 105 °C, nitrogen gas volume, no field stress).

Modell	tan δ/‰ first measurement at 90 °C	tan δ/‰ actual measurement at 90 °C	Δ tan δ/‰ at 90 °C	Average Δ tan δ/‰ at 90 °C
N_105_E0_04	2,40	3,24	0,84	**1,35**
N_105_E0_21	2,67	4,02	1,35	
N_105_E0_24	2,79	4,65	1,86	

4.2. Influence of the temperature

The expected result that higher temperatures cause an accelerated ageing of the insulation could be confirmed in all measurements. E.g. Fig. 8 shows the comparison of 3 groups with nitrogen gas volume (N) and without electrical stress (E0) for 3 different ageing temperatures, but at the same measuring temperature.

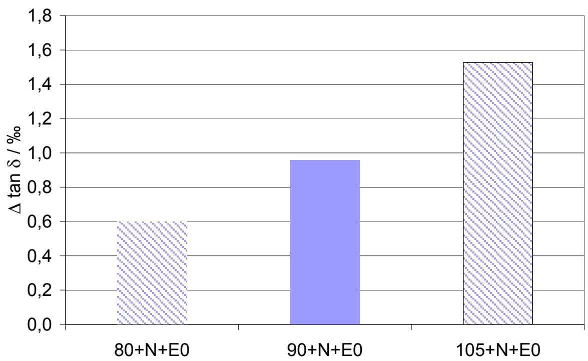

Figure 8: Dissipation factor change of different temperature groups with nitrogen gas volume and without electrical stress (each consisting of 3 models) after about 150 days of thermal stress at ageing temperature, measurement at 90 °C.

4.3. Influence of the air

If models with hermetically sealed nitrogen gas volume are compared with models which allow some exchange of their air volume with the environment, significant differences can be seen for measurements at the same temperature, Fig. 9. Dissipation factor increases are stronger for air-filled models. Possibly this is partly caused by the oxygen and partly by air humidity. Both factors accelerate oxidative processes of oil and cellulose. These processes are significantly slower under a nitrogen atmosphere.

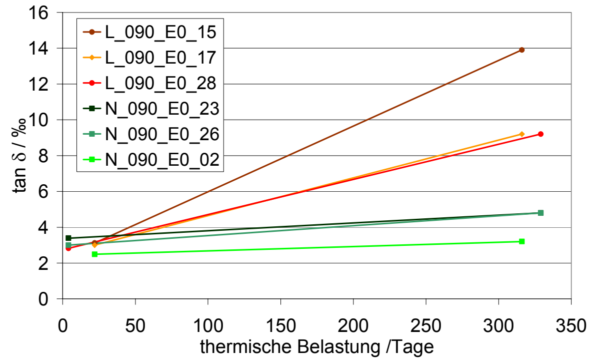

Figure 9: Dissipation factor changes for models with nitrogen (N) or air (L) volume without electrical field strength after 300 days of thermal stress at 90 °C, measurement at 90°C.

4.4. Influence of the field strength

Models with and without fields stress are compared in Fig. 10. The influence of electrical field stress on ageing can clearly be recognized. This influence has not been expected so before. It is not probable that the electrical field splits the connections of the cellulose or the oil molecules at E = 4 kV/mm. On the other hand, there are significantly higher field strengths at the edges of the foils. The influence of field strength can also be seen at 80 and 90 °C for the models with air volumes. For the slower ageing models with nitrogen gas volumes the effect of field strength can not yet be proven.

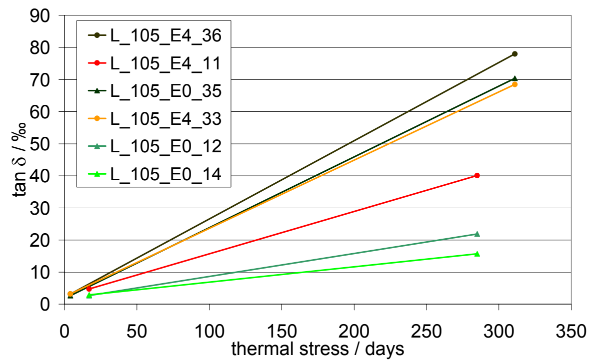

Figure 10: Dissipation factor change of models with air volumes with (E4) or without (E0) electrical field strength after 300 days of thermal stress at 105 °C, measurement at 90 °C.

4.5. Comparison of PDC and dissipation factor measurements

In former publications it was shown, that the measurement of polarisation and depolarisation currents (PDC) can be used to detect ageing and moisture already at room temperature (RT) [10]. This is not possible for tan δ measurements. Furthermore it is possible to get additional information about the condition of the insulation with PDC measurements [11]. Therefore the changes of the dissipation factor should be compared to the changes of the conductivity κ which was calculated with the help of the charge difference method [12] from PDC measurements.

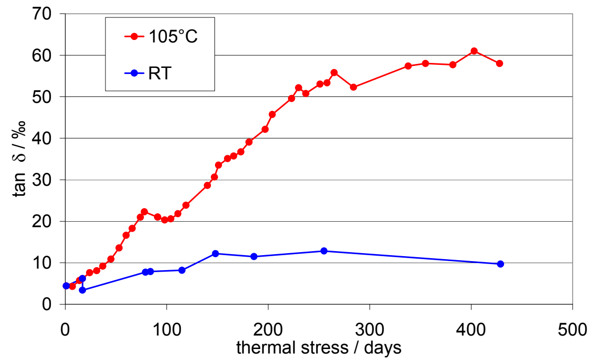

Figure 11: Dissipation factor changes for model no. 11, measurements at 105 °C and at RT.

Conductivity changes are compared with dissipation factor changes, both at RT and at 105 °C, Fig.s 12 and 13. It can clearly be seen, that the conductivity values change more than dissipation factor values. Obviously, conductivity values (calculated from PDC measurements) are much better indicators of ageing. Especially at RT conductivity measurements indicate ageing with significantly higher sensitivity than dissipation factor measurements, Fig. 12.

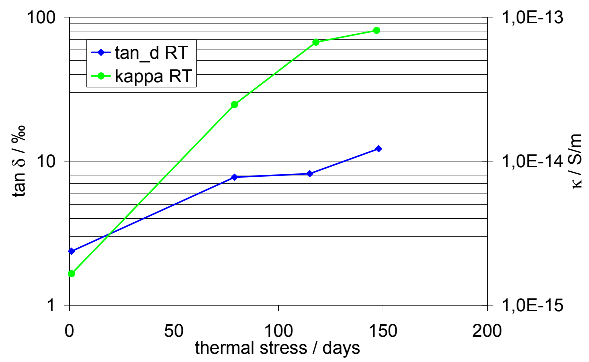

Figure 12: Changes of dissipation factor and conductivity for model no. 11, measurements at RT.

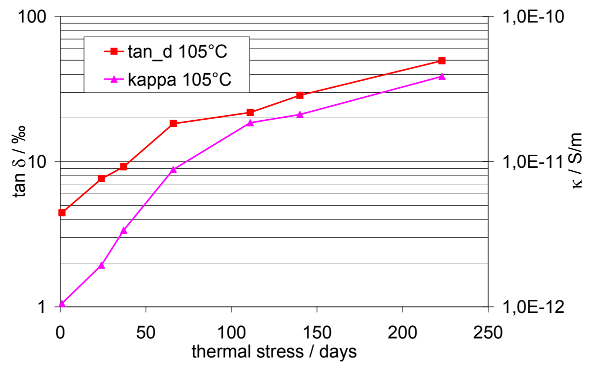

Figure 13: Changes of dissipation factor and conductivity for model no. 11, measurements at 105 °C.

These statements are also confirmed by the comparison of the Fig.s 10 and 14: The dissipation factor is a sensitive indicator for the ageing at high temperatures only, Fig. 11. The conductivity changes are nearly independent from temperature, Fig 14.

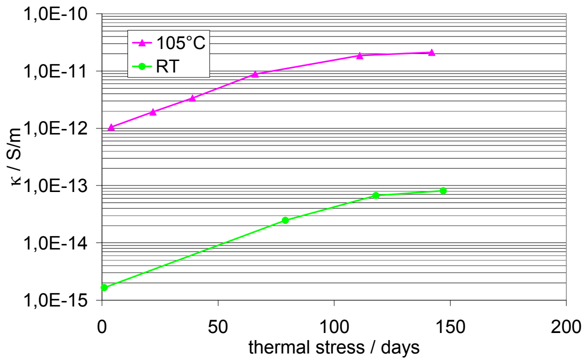

Figure 14: Conductivity changes for model no. 11, measurements at 105°C and at RT.

These differences show, that the dissipation factor at room temperature is not very suitable for dielectric diagnosis. Significant changes of the dissipation factor at high temperatures are reduced to small changes at RT [13]. Therefore dielectric diagnoses of bushings require either on-line monitoring at elevated service temperatures or off-line diagnosis with PDC [12].

5. CONCLUSIONS

A new solution for the on-line monitoring of capacitance C and dissipation factor tan δ was presented in this paper.

Signals are taken from the measuring or potential tap of the bushing and compared with the signals from a reference unit. Advanced digital signal processing allows to calculate capacitances and dissipation factor changes with high accuracy. Influences of noise, harmonics, changing voltages, temperature variations in the circuits and wetting of the reference unit are successfully excluded.

Measured dissipation factor values have to be related to known ageing conditions. Therefore experimental investigations on the ageing processes in OIP have been started. Thereby a better understanding of on-line monitoring information will be possible.

The ageing investigations on OIP bushing models show continuously increasing values of dissipation factor and conductivity. The change in the dielectric properties is mainly caused by the ageing of the oil and not by the ageing of the paper [12].

A strong influence of temperature and access of air can be observed. Furthermore, there is an influence of electric field stress on ageing. These influences can be explained by the access of oxygen and water through the air and by very high local field strengths at the edges of the aluminium foils.

The measurements on aged bushing models are in good correlation with experiences from service aged bushings [12]. Ageing at very high temperatures is significantly accelerated in comparison to service temperatures.

Furthermore, it could be recognized that ageing can be determined from dissipation factor measurements at higher temperatures. Ambient temperature is not enough. Supervision of bushings requires on-line monitoring at higher service temperatures therefore.

In contrast to this, ageing progression can be determined with polarisation and depolarisation current (PDC) measurements already at room temperature.

All cases of slow continuous or fast and sudden ageing processes can clearly be recognized with an on-line dissipation factor monitoring [14], but not with traditional off-line dissipation factor measurements at ambient temperature.

6. ACKNOWLEDGMENT

The authors gratefully acknowledge financial support of this work by the German Federal Ministry of Education and Research (Bundesministerium für Bildung und Forschung, BMBF 17 45A 04).

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