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CONDITION ASSESSMENT OF AGED TRANSFORMER BUSHING INSULATIONS

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SUMMARY

Transformer failures are often related to bushings with oil-impregnated paper (OIP) insulation. Therefore a strong need for reliable condition assessment exists, but problems are to be solved:

(1) Traditional diagnosis consists of C/ tan δ measurements at the potential tap of the bushing, but relations between insulation conditions (e.g. moisture and ageing) and diagnostic quantities are uncertain. Tan δ at service temperatures is unknown (although possibly high and dangerous). A significant improvement is achieved by polarisation/ depolarisation current measurements (PDC measurements), even at ambient temperatures. A new evaluation method is proposed, the so called charge difference method CDM. It allows calculation of d.c. conductivities very quickly within some minutes.

(2) Laboratory tests on wetted OIP samples show the dependence of dielectric properties (expressed by PDC) on temperature, moisture and oil conductivity. D.c. conductivity in OIP is strongly related to **moisture** content, and - to a smaller extent - to oil conductivity and ageing. **Ageing** mainly influences short term polarisation currents because of increased **oil conductivity**.

(3) **Strongly aged 420 kV OIP bushings** could be identified with PDC analysis at room temperature, although there was no indication of defects from C/ tan δ values. Measurements at service temperature revealed the danger of thermal instabilities, partial discharges and breakdown. PDC analysis is the first known dielectric method for identification of significantly aged OIP at room temperature.

(4) It is not always correct to relate measurements to the core of the bushing only. Signals can be influenced by **parasitic currents** with access to grading foils. Theory, measurements and simulations show that tan δ and PDC can (apparently) be increased, reduced or reversed in polarity. Influences are weak for aged and strong for new bushings. Measurements with conductive bandages give lower and upper limits and guarded signals. Therefore it is proposed to measure with "worst case" and "guard ring bandages" in order to make improved estimations of currents related to the insulation core.

It is proposed to distinguish influences of ageing, moisture and environment by PDC analysis: Ageing can be detected from short term currents even at ambient temperature. OIP d.c. conductivity contains information both about moisture and ageing, it can be calculated by a new charge difference method CDM. External influences have to be considered by means of bandages on the bushing surface.

KEYWORDS

Bushing - Diagnosis - Dissipation - tan δ - Polarisation - Depolarisation - PDC - Conductivity - Oil-Impregnated Paper - OIP - Moisture - Ageing.

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1 INTRODUCTION

1.1 Problem

A significant percentage of transformer failures is related to bushing insulation defects already today. In the future an increasing number of progressively ageing oil-impregnated bushings will be subjected to increasing thermal stresses due to increasing power flow requirements and overloading conditions. Therefore a strong need for reliable condition assessment of strategically important bushings will arise. It is a challenging task

- to find dielectric measurement procedures which are sensitive to insulation quality,
- to establish correlations between diagnostic signals and insulation conditions and
- to develop evaluation procedures which avoid parasitic influences.

1.2 Bushing Diagnosis

Today dielectric diagnosis of bushings is based on off-line power frequency measurements of capacitance C and dissipation factor tan δ at the potential tap which is connected to the outermost grading foil. The bushing **capacitance** is a sensitive quantity for the detection of partial breakdowns between grading foils. Unfortunately, capacitance does not change significantly during slow ageing processes of oil impregnated paper OIP. Only severe degradation of the insulation, just before total breakdown, is indicated. Therefore capacitance measurement does not give any certainty during offline measurements, but it is a good emergency indicator within an online monitoring system. During offline measurements, when **dissipation factors are** measured at ambient or room temperature, the values are low and insignificant, even for strongly aged or wet insulation. Dissipation factors at service temperatures above 50 °C remain unknown, although they might be high and indicate dangerous thermal instabilities. Therefore it is desirable to measure tan δ online at service temperature by a monitoring system or to find dielectric measurements which indicate ageing and high water content during offline measurements at ambient temperature. Offline diagnosis at elevated temperatures is not possible normally.

1.3 Dielectric Measurements, PDC Analysis

Dielectric measurements can be performed in the frequency domain (FDA **f**requency **d**omain **a**nalysis) or in the time domain (PDC **p**olarisation and **d**epolarisation **c**urrents). For linear systems both methods are mathematically equivalent [1], [2], [3]. The authors decided to use PDC analysis because of the following reasons:

- Basically PDC measurements give step responses containing the whole system information.
- PDC allow to calculate d.c. conductivities containing information about moisture and ageing [4].
- Currents at different times are related to different influences [5] (e.g. oil quality, ageing, moisture).
- Time domain signals can be observed easily, explained by physical models (ion movement in oil) and described clearly (ion transit times) [6].
- PDC analysis has been successfully applied to transformer diagnosis [7], [8], [9].
- Procedures have been developed to extract relevant information from very short measurements.

2 PDC ANALYSIS AND CHARGE DIFFERENCE METHOD CDM

2.1 PDC Analysis

PDC analysis is based on curve fitting today. I.e. a polarisation current $i_p(t)$, measured at a voltage step U during a charging time t_C, and a depolarisation current $i_d(t)$, measured at the subsequent grounding, are fitted with a number of exponentially decreasing currents $i_j(t)$ which are related to a number of parallel R_jC_j series elements with $\tau_j = R_jC_j$:

$$i_p(t) \quad = \sum_j i_j(t) + i_\infty \quad = U \cdot \sum_j \left(\frac{1}{R_j} e^{-t/\tau_j}\right) \quad + \quad \frac{U}{R_\infty} \qquad \text{for } t < t_C \tag{1}$$

$$i_d(t) \quad = \quad -U \cdot \sum_j \frac{1}{R_j}(1-\mathrm{e}^{-t_C/\tau_j}) \cdot \mathrm{e}^{-(t-t_C)/\tau_j} \qquad \text{for } t > t_C \tag{2}$$

Thereby an equivalent circuit is generated describing linear material properties both in time and frequency domain [10]. Different time constants $\tau_j = R_j C_j$ are correlated with different polarisation processes, the long term (end) value U/R_∞ is determined by the so called d.c. conductivity κ which is an important diagnostic quantity, but which is difficult to evaluate because of very long lasting polarisation processes. In this paper the term "conductivity" is always used to describe d.c. conductivity, determined from long term PDC measurements converging towards theoretical end values.

A better convergence is achieved, if the sum of polarisation and depolarisation currents (i.e. the difference of the current amounts) i_p and i_d is regarded. i_p is flowing after the voltage step at $t > 0$, i_d is flowing after the charging time $t > t_C$ (i.e. after the end of voltage application). Therefore $i_d(t)$ is shifted to $i_d(t+t_C)$ by the charging time t_C [11]:

$$i_p(t) \ + \ i_d(t+t_C) \ = \ \sum_j \left(\frac{U}{R_j}\mathrm{e}^{-(t+t_C)/R_j C_j}\right) \ + \ \frac{U}{R_\infty} \tag{3}$$

Eq. (3) gives a better approximation of the long term (end) value U/R_∞ than eq. (1) because of increased exponents, fig. 1 (left).

2.2 Charge Difference Method CDM

Sometimes currents and evaluations are disturbed by noise. Therefore a new charge difference method CDM was developed which is less sensitive to noise. It uses charges from the integration of measured polarisation and depolarisation currents [12], fig. 1 (right):

$$q_p(t) \quad = \ U \cdot \sum_j C_j(1-\mathrm{e}^{-t/\tau_j}) \quad + \quad \frac{U}{R_\infty} \cdot t \tag{4}$$

$$q_d(t+t_C) \ = \ -U \cdot \sum_j C_j(1-\mathrm{e}^{-t_C/\tau_j})(1-\mathrm{e}^{-t/\tau_j}) \tag{5}$$

The *first* quantity $q_p(t)$ is the **total amount of charge**, flown during a time t, eq. (4). It is caused by polarisation processes (which store charge) and by d.c. conduction (which does not store charge). The long term value of the gradient U/R_∞ is proportional to the d.c. conductivity κ. The *second* quantity $q_d(t+t_C)$ gives the **stored charge** which is delivered by (de)polarisation processes within the test object during a time t following the charging time t_C, eq. (6). The long term value approaches the amount of charge $q_d(\infty) = -U \cdot \Sigma_j C_j \cdot \{1 - \exp(-t_C/\tau_j)\}$which was stored during the preceding charging time t_C.

A *third* quantity is defined as sum of charges q_p and q_d (i.e. as difference of the charge amounts). It describes the **charge which is not stored**:

$$q_p(t) + q_d(t+t_L) \quad = \quad U \cdot \sum_j C_j \cdot \mathrm{e}^{-t_C/\tau_j}(1-\mathrm{e}^{-t/\tau_j}) \ + \ \frac{U}{R_\infty} \cdot t \tag{6}$$

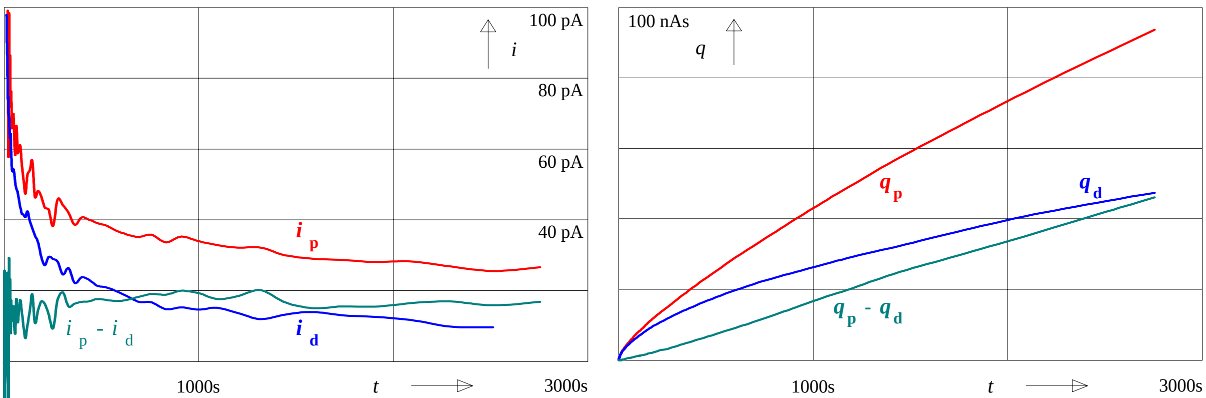


Fig 1: PDC measurement on OIP bushing no. (3) from fig. 7 (left): Currents and current differences, CDM charge difference method (right): Total charge q_p, stored charge q_d and non-stored charge q_p-q_d.

For long times the gradient U/R_∞ is proportional to the d.c. conductivity κ. It was found from measurements, that charge difference curves show straight lines, i.e. constant gradients already after comparatively short times of a few 1000 s, fig. 1 (right). Therefore good approximations of U/R_∞ and κ can be achieved within short measuring times and noise is filtered by the preceding integration.

3 PROPERTIES OF OIL-IMPREGNATED PAPER

Measurements on transformer insulation OIP samples show, that both the presence of water and ageing effects influence dielectric properties [13]. In order to investigate material properties of bushings, PDC measurements were performed on vacuum impregnated OIP samples with two different oils (oil 1 and oil 2), different water contents, temperatures and field strengths and on service aged OIP bushings. The d.c. conductivities were calculated with the new charge difference method.

3.1 Experiments on Laboratory Samples

With respect to real insulations, samples were dried and impregnated first and wetted afterwards: Samples were formed from Kraft paper layers (12 x 100 µm, density approx. 0.65 g/cm^3), supported on a stainless steel helix in a stainless steel vessel, dried under vacuum/ temperature and impregnated under vacuum, fig. 2 (left). Afterwards a small amount of water was deposited with a µl-syringe underneath the paper on the bottom. In order to transfer the water from the droplets into the impregnated paper the closed vessel was exposed to thermal cycles followed by a waiting period at 60 °C. Some reference samples were used to check by Karl-Fischer-Titration KFT that the moisture transfer was complete, that the water content was as predicted from equilibrium curves and that the moisture distribution was uniform in all three dimensions.

Prior to a measurement, top and bottom layers were removed in order to check the water content with KFT. The ten remaining layers, constituting a dielectric sample, were measured between stainless steel guard ring electrodes in a glass vessel immersed in oil in which the sample had been wetted and stored, fig. 2 (right). A measuring cycle consisted of a C/ tan δ measurement at 2 kV/mm, 50 Hz and two PDC measurements [6] at two field strengths (0.1 - 1 kV/mm) and at three temperatures (room temperature RT - 50 °C - 90 °C). Finally the moisture content of centre layers was cross-checked with KFT. A number of measuring cycles was performed with differently wetted samples and with two different oil qualities. Oil 1 had a lower and oil 2 had a higher conductivity.

3.2 Results from OIP Samples

<u>**(1) Oil 1:**</u> Increasing **temperatures** cause exponentially increasing polarisation currents, time constants are shifted towards shorter times, fig. 3 (left). PDC measurements allow to calculate d.c. conductivities by the charge difference method CDM. Many results are summarized in fig. 3 (right): Increasing **water content** causes increasing conductivities for all temperatures. Conductivities at 50 and

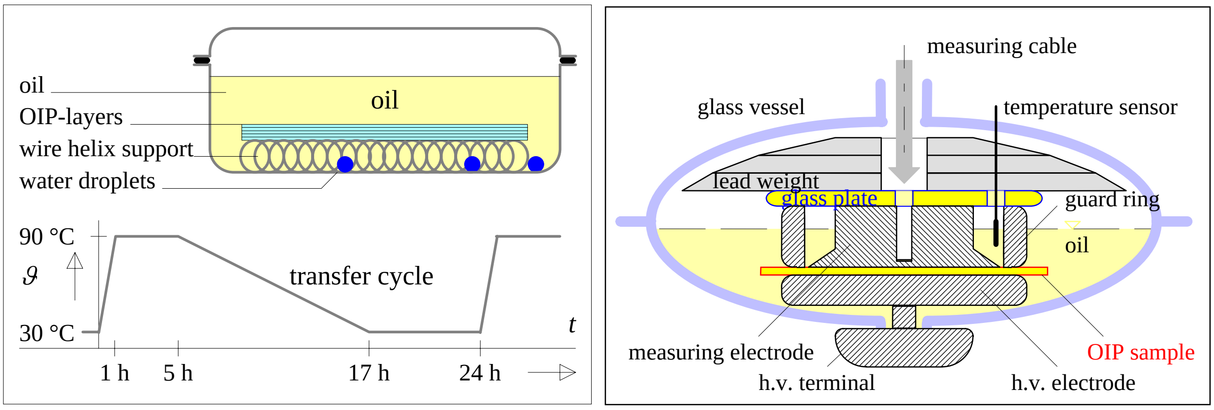


Fig. 2: Defined and uniform wetting of vacuum impregnated OIP samples by moisture transfer (left) and measurement of wetted OIP samples between guard ring electrodes (right).

90 °C are used to calculate RT values (empty symbols) by Arrhenius' law $\kappa = \kappa_0 \cdot \exp(-W_a/kT)$ with activation energy W_a and Boltzmann constant k. A very good agreement with directly measured values (filled symbols) is achieved in the whole range of technical relevant moisture contents. Two conclusions are drawn:

1. At room temperature, even long before PDC measurements can reach constant end-values, the charge difference method CDM allows to evaluate d.c. conductivity values correctly.
2. If the temperature is known, PDC measurements can be normalized to a reference temperature.

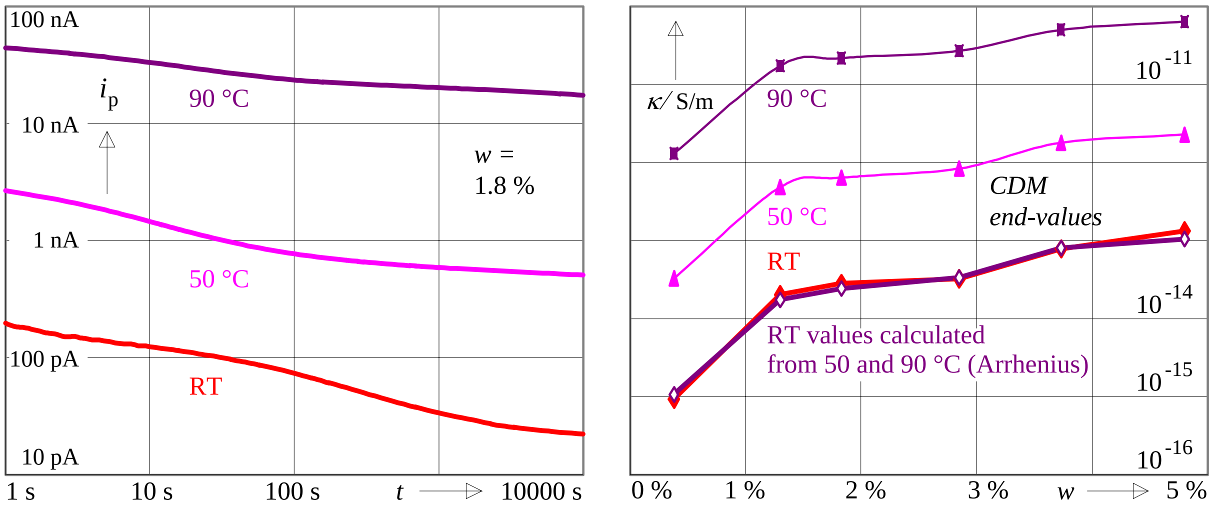


Fig.3: Polarisation currents at different temperatures through OIP samples with 1.8 % water (left) and d.c. conductivities calculated from charge differences (CDM values) as function of temperature and water content (right). RT values are additionally calculated from 50 and 90 °C for verification of Arrhenius' law (right, empty symbols). E = 0.1 kV/mm, oil no. 1.

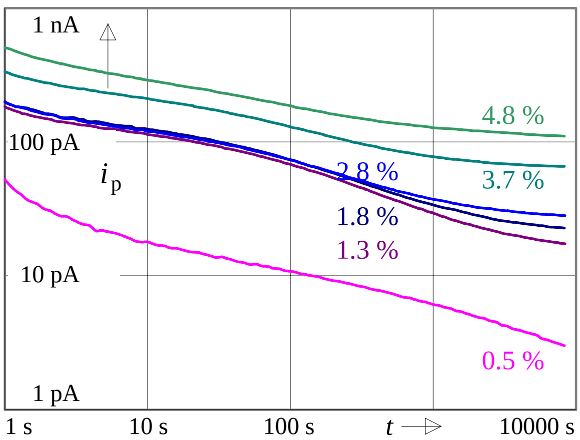


Fig. 4: PDC: *Polarisation currents* for different water contents through OIP samples at room temperature RT and 0.1 kV/mm, oil no. 1 (compare with fig. 5 top).

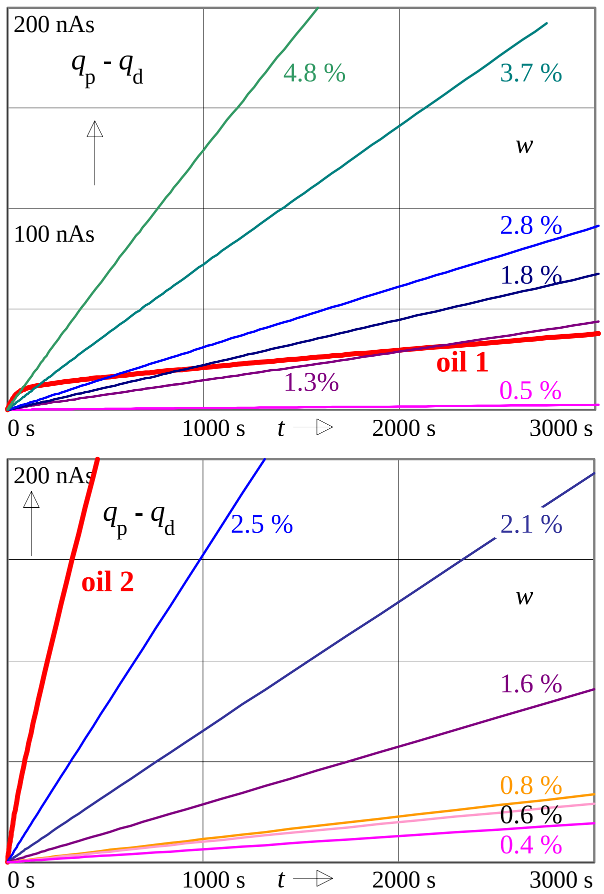


Fig. 5: CDM: *Charge differences* for different water contents in OIP samples, impregnated with a high resistive oil 1 (top, compare fig. 4) and with a low resistive oil 2 (bottom) at RT and 0.1 kV/mm. Gradients are proportional to d.c. conductivities of OIP and oil (thin and thick lines).

Generally it is possible to distinguish different water contents with PDC measurements directly, fig. 4. Best differentiation is given for long measuring times. For short times < 300 s no differences were observed between 1.3 and 2.8 %.

If the charge difference method CDM is applied to the same data, different water contents can be distinguished very clearly, fig. 5 (top). The CDM curves turned out to be straight lines with gradients proportional to the d.c. conductivity which normally can only be measured after very long times >> 10000 s. These gradients were used to determine RT conductivities in fig. 3 (right, filled symbols).

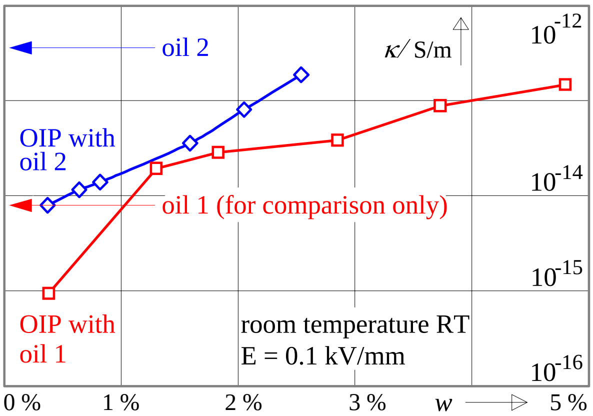


Fig. 6: Influence of d.c. oil conductivity and water content on d.c. conductivity of OIP samples.

<u>**(2) Oil 2:**</u> Another important dependence was observed: The OIP conductivity is significantly influenced by the **oil conductivity**. A high resistive oil 1 (d.c. conductivity $7.9 \cdot 10^{-15}$ S/m at 0.1 kV/mm) and a low resistive oil 2 ($3.6 \cdot 10^{-13}$ S/m) caused significantly different OIP conductivities at the same moisture level, fig. 5 (top and bottom) and fig. 6. Again two conclusions are drawn:

1. High OIP conductivities can be caused both by water content and by high oil conductivity as it might be generated during ageing processes. I.e. the dielectric diagnosis needs further information in order to differentiate the influence of both parameters during PDC analysis.
2. The conductivity ratio between oil and solid insulation is strongly dependent on the water content. I.e. dry OIP has a low and wet OIP has a high conductivity in comparison with oil. This is especially important in the case of HVDC insulations.

3.3 Aged Bushings

The properties of aged OIP were investigated on identical 420 kV OIP bushings which have been operated for approx. 10 years without partial breakdowns, fig. 7. The old core of bushing no. (4) was replaced. PDC measurements and gas-in-oil analyses were performed on all bushings. Measurements of tan δ at elevated temperatures and measurements of water contents were performed on selected bushings, table 1. According to gas-in-oil analysis no.s (1) and (5) had partial discharges (p.d.) which was confirmed in laboratory tests. Tan δ measurements at 70 and 80 °C show that these objects had a strongly aged insulation with high dielectric losses at service temperature. Therefore p.d. might have been caused by a thermal instability, overheating and gassing. Interestingly PDC measurements are able to classify severely and normally aged bushings in the same order, even at room temperature!

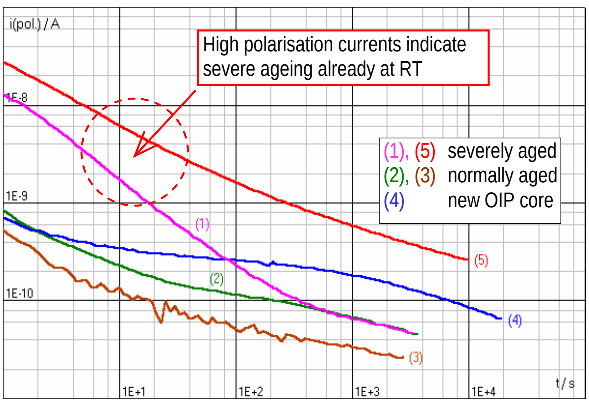


Fig. 7: PDC measurements on identically designed 420 kV OIP bushings, differently aged in service, measurement at RT and 1 kV.

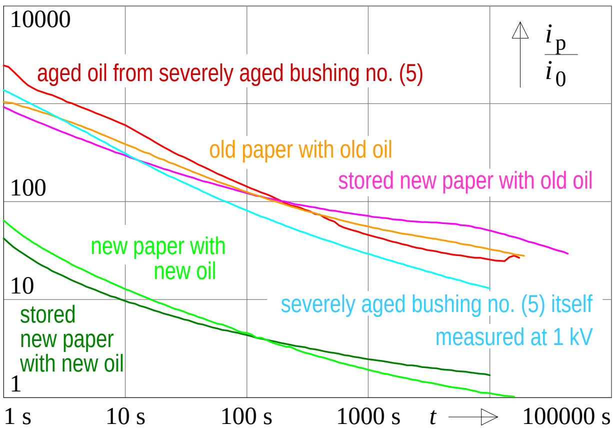


Fig. 8: Influence of service aged oil on polarisation currents in OIP. Currents are normalized to the same capacitance, measured at RT and 1 kV/mm.

Table 1: Differentiation of ageing and enhanced water content for service aged 420 kV OIP bushings by PDC analysis at room temperature. Unequivocal PDC results are underlined in blue coloured cells.

Bushing No.	**Gas -in-oil**	**tan δ** (50 Hz) at elevated temperature	**PDC** (at room temperature, t = 1 s and 1000 V)	Water in oil at 70°C	**KFT** on paper sample	**PDC-analysis** moisture and ageing indicator
(1)	**p.d.**	**1.6 %** (oven at 80°C)	**13 nA** →**"severely aged"**			**0.65 %** → **"dry"**
(2)	**ok**		0.9 nA			**0.65 %** → **"dry"**
(3)	**ok**	0.2 % (oven at 80°C)	0.5 nA			**< 0.5 %** → **"dry"**
(4)	**ok**		0.7 nA			**< 1 %** → **"dry"**
(5)	**p.d.**	**1.9 %** (oven at 70°C) 6.1 % (paper sample at 70°C)	**27 nA** →**"severely aged"**	6 ppm (KFT)	**0.3 ... 0.8 %**	**2.4 %** → **ageing or moisture**

Obviously the severely aged bushings (1) and (5) can be detected from significantly enhanced polarisation currents within some ten seconds, fig. 7 and table 1. These currents are caused by additional polarisation processes related to ageing products. Independently from their ageing conditions bushings no.s (1) ... (4) are classified by PDC analysis to be "dry" because of low d.c. conductivities [10], [14]. No. (5) has a higher d.c. conductivity which might be related to a water content of 2.4 % if the oil is high resistive [5], [10]. On the other hand it is known that no. (5) is severely aged and that low resistive oil enhances OIP conductivities. Therefore additional measurements of water content in oil have been performed and OIP samples were cut. Both showed that this bushing remained in a dry condition too, table 1.

- It is concluded that PDC analysis can be used to distinguish ageing and enhanced water content of OIP. Unequivocal results are underlined in table 1 (blue coloured cells).
- **Severely aged OIP** insulations can be **detected with PDC** measurements already at **room temperature**, which is not possible with power frequency tan δ measurements!

It is supposed that ageing mainly influences the dielectric properties of the oil component in OIP. This was investigated on samples with different papers impregnated (resp. immersed) in new oil and in aged oil taken from bushing no. (5), fig. 8. Polarisation currents measured on an aged bushing can be reproduced, if the aged oil is used both with new and aged paper. If new oil is used, polarisation currents are smaller by one order of magnitude.

- Obviously aged oil has a dominant influence on polarisation currents in OIP.

4. EXTERNAL INFLUENCES

In chapter 3 it is assumed that dielectric measurements on bushings can directly be related to the OIP bushing core. This is not always true: It is reported that leakage currents from the grading foils to ground are responsible for "negative dissipation factor measurements" [15] and it is assumed that polarity reversals during polarisation current measurements are caused by leakage currents [16]. Therefore it was investigated under which conditions correct dielectric measurements on bushing are possible.

4.1 Basic Theory

In order to explain the effect, a bushing core is described by two capacities C_a and C_b and one grading foil in-between, fig. 9 and 10. A conductive path is assumed from ground or h.v. to the grading foil (left and right). In the **frequency domain** the influence of the conductive path can be described by a phase shift between measured current $\underline{I}_b$ and applied voltage $\underline{U}$ which can be bigger or smaller than 90°, fig. 9 (left and right). Thereby the dissipation factor appears to be negative or positive. Notice: It is an apparent effect, in reality the ideal capacitance does neither produce nor dissipate energy [17]. For the description in **time domain**, additional elements are introduced to the equivalent circuit in order to consider polarisation and conductivity, fig. 10. The influence of the conductive path can be described analogously by a reduction or an enhancement of the measured current $i_b(t)$, fig. 10 (left and

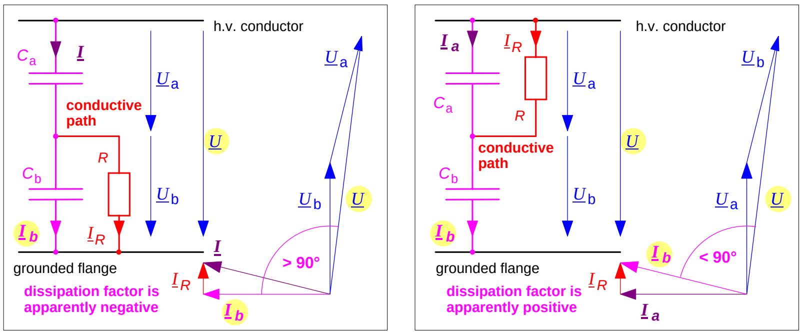


Fig. 9: Frequency domain: A conductive path from a bushing grading foil to ground or h.v. (left and right) results in apparent reduction or enhancement of dissipation factor tan δ.

The bushing core is described by series capacities C_a and C_b.

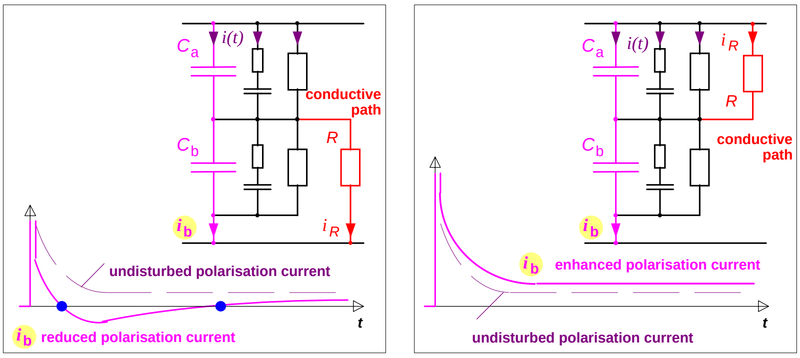


Fig. 10: Time domain: A conductive path from bushing grading foils to ground or h.v. (left and right) results in reduction or enhancement of polarisation current. Even polarity reversals are possible (left).

The bushing is described by C_a, C_b and additional elements (polarisation and conductivity).

right). A conductive path to ground can result in a temporary discharging of C_b, in a negative current i_b and in two polarity reversals, fig. 10 (left).

4.2 Measurements and Simulations

External influences – as described above - were investigated by a set of three measurements at the potential tap of a bushing, fig. 11: (1) The traditional measurement without bandages, (2) a measurement with a circumferential **bandage** in the **middle of the grading contour** at ground potential and (3) a measurement with the same bandage at diagnostic voltage (h.v.).

- Measurement (1) gives an estimation of the current through the bushing's OIP core.
- Measurements (2) and (3) impose extreme values of parasitic surface currents. Therefore the measured currents can be interpreted as **lower and upper limits** of the current through the bushing's OIP core, fig. 12 (top left). The bandages can be called **"worst (extreme) case bandages"** showing the sensitivity of the bushing to parasitic currents.

The behaviour of the bushing with and without bandages was simulated with a network model. The nodes of the model were meshed in axial and radial orientation [17]. Every connecting element consisted of capacitance (replacing permittivity), resistance (replacing conductivity) and RC-elements (replacing different polarisation processes). These equivalent circuits, describing the local materials, were

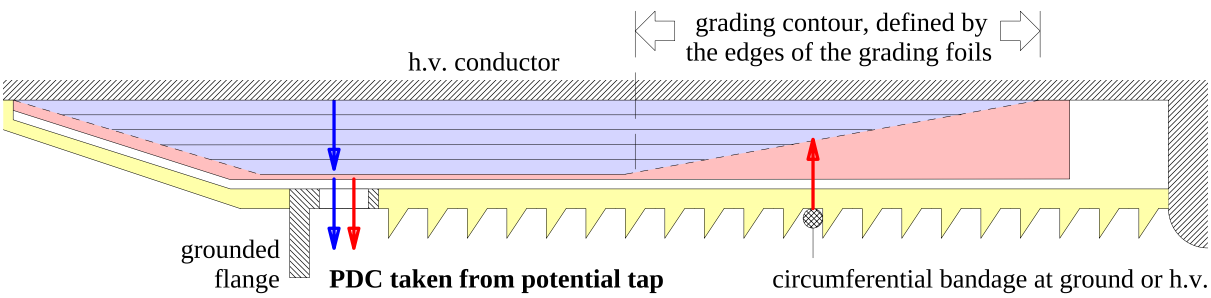


Fig. 11: PDC measurement at the potential tap of a bushing with a circumferential bandage in the middle of the grading contour, connected either to ground or to diagnostic voltage (h.v.).

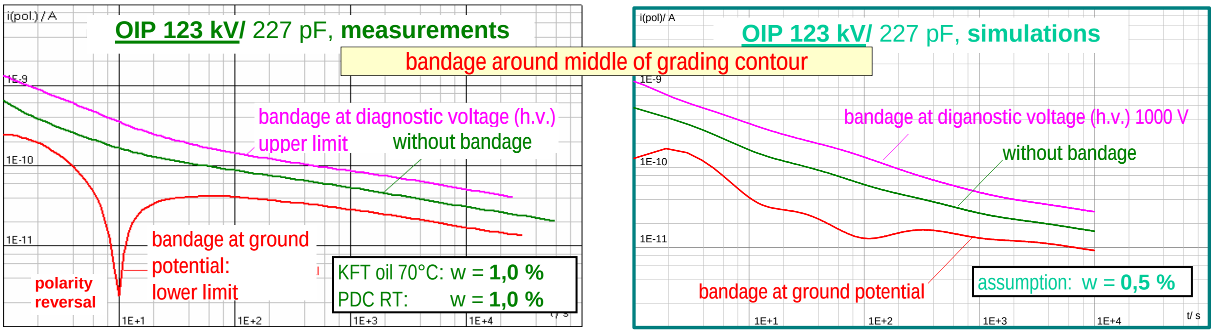
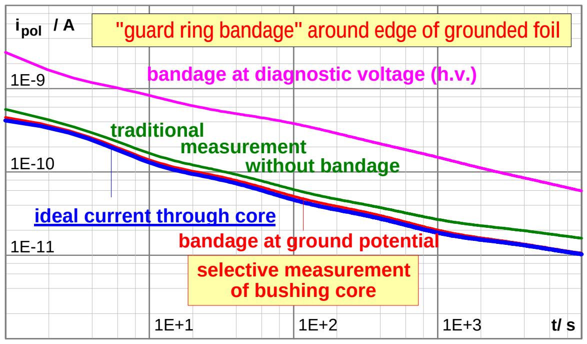


Fig. 12: PDC measurements without and with bandages in the middle of the grading contour. Bandages at h.v. and ground give upper and lower limits for polarisation currents through the bushing's core (**worst case bandages**), measurements (*top left*) and simulations (*top right*).



If bandage is situated above the edge of the grounded foil, PDC measurement is identical with the idealised current through a pure OIP core (**guard bandage**), see simulations (*right*).

derived from PDC measurements on material samples for all materials used in a bushing. The results of simulations are in good agreement with measurements, fig. 12 (top right and left). Only small current differences could be observed, probably because material samples and bushing materials are not absolutely identical. The bushing was a spare object and stored for 10 years.

The simulation model, which proved to be in good agreement with measurements, was used to optimise the position of the bandage. It was found, that

- a grounded **bandage** above the **edge** of the **outermost layer** on the air side of the bushing

collects all relevant leakage currents on the air side of the bushing. It can be called **"guard ring bandage"** protecting the measurement. The current taken from the potential tap is therefore identical with the current through the **bushing's core**, fig. 12 (bottom right).

It was further investigated whether the **oil conductivity of the transformer** might cause leakage currents which are not collected by a guard bandage on the air side and which can influence the measured currents. The result is, that there is no influence for long term values because of the high resistive epoxy housing insulator on the transformer side. For shorter times there is a capacitive coupling from the transformer oil to grading layers on the transformer side. Therefore it is advisable

- to base analysis on long term values as they are calculated with the charge difference method CDM.

Another result of these investigations is that power frequency dissipation factors tan δ are influenced in a similar way, but to a smaller extend [17].

4.3 Application on Bushings

Bandages in the middle of the grading contour give lower and upper limits for the polarisation current through the bushing's core. If the bushing is new, these limits are clearly separated, fig.

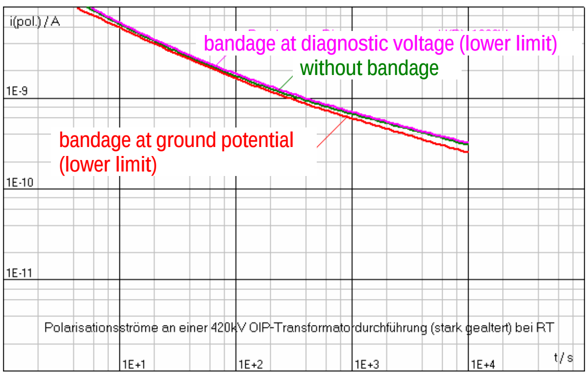


Fig. 13: Polarisation currents measured on a severely aged 420 kV OIP bushing no. (5) in fig. 7 and table 1, measured at RT and 1 kV.

12 (top). In the case of severely aged bushings, currents are strongly enhanced and leakage currents are negligible, fig. 13. The upper and lower limits are close together and the traditional measurement without bandages can be considered to be correct.

5. CONCLUSIONS

(1) **PDC analysis** is a powerful tool for the evaluation of OIP-bushings and other oil impregnated insulations. It can be further improved by the **charge difference method CDM**. CDM is insensitive to noise and gives quick estimations for d.c. conductivities which contain important information about the dielectric properties.

(2) **Dielectric properties of OIP** were investigated with PDC measurements on uniformly wetted samples as function of temperature, water content and oil conductivity:

Temperature dependence fits to Arrhenius' exponential law. Therefore d.c. conductivities, which often cannot be determined at RT within acceptable measuring times can be calculated from measurements at elevated temperatures. Alternatively a calculation with the new CDM is possible.

Moisture in OIP causes a strong increase of the d.c. conductivity values. They are further dependent on **oil conductivity**. Therefore PDC analysis is sensitive to two concomitants of ageing, i.e. to wetting and degradation of oil quality.

Severe ageing of OIP especially causes high values of polarisation currents in an early phase during some hundred seconds after beginning of polarisation. Thereby severely aged bushings (which had critical dielectric losses at service temperature and which had partial discharges) could be **identified by PDC measurements** already **at room temperature!** This is not possible with power frequency tan δ measurements.

It could be shown that ageing of OIP is strongly related to the ageing of oil which causes increased oil conductivity which, in turn, causes enhanced polarisation currents.

(3) **Bushing core properties** can not be measured correctly, if parasitic currents have access to the grading foils. Thereby dissipation factors (frequency domain) and polarisation currents (time domain) can be increased or reduced apparently.

It is proposed to use **conductive bandages** above the grading contour to determine the sensitivity of the bushing against external influences. With two additional measurements (bandage at ground potential and at diagnostic voltage) **lower and upper limits** can be found for polarisation currents (worst/ extreme case scenarios).

Network optimisation showed that the pure **bushing core current** is measured, if a grounded bandage is situated above the edge of the grounded layer (guard ring effect).

Such a guarding bandage can only be used on the **air side** of the bushing. Parasitic currents on the **transformer side** are blocked by a high resistive housing insulator, but only for long measuring times. Therefore again it is proposed to consider d.c. conductivity values derived from CDM.

PDC measurements on severely aged bushings and power frequency measurements are almost not sensitive to parasitic currents.

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