51. IWK

Internationales Wissenschaftliches Kolloquium

International Scientific Colloquium

PROCEEDINGS

11-15 September 2006

FACULTY OF ELECTRICAL ENGINEERING AND INFORMATION SCIENCE

INFORMATION TECHNOLOGY AND ELECTRICAL ENGINEERING - DEVICES AND SYSTEMS, MATERIALS AND TECHNOLOGIES FOR THE FUTURE

TECHNISCHE UNIVERSITÄT
ILMENAU

Impressum

Herausgeber: Der Rektor der Technischen Universität Ilmenau
Univ.-Prof. Dr. rer. nat. habil. Peter Scharff

Redaktion: Referat Marketing und Studentische Angelegenheiten
Andrea Schneider

Fakultät für Elektrotechnik und Informationstechnik
Susanne Jakob
Dipl.-Ing. Helge Drumm

Redaktionsschluss: 07. Juli 2006

Technische Realisierung (CD-Rom-Ausgabe):
Institut für Medientechnik an der TU Ilmenau
Dipl.-Ing. Christian Weigel
Dipl.-Ing. Marco Albrecht
Dipl.-Ing. Helge Drumm

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

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

ISBN (Druckausgabe): 3-938843-15-2
ISBN (CD-Rom-Ausgabe): 3-938843-16-0

Startseite / Index:
http://www.db-thueringen.de/servlets/DocumentServlet?id=12391

A. Kuechler[1], F. Huellmandel[1], K. Boehm[1], M. Liebschner[1], M. Appold[1],
R. Krump[2] and J. Titze[2]

Dielectric Diagnosis and Monitoring of High Voltage Bushings

ABSTRACT

Dielectric diagnosis and monitoring of high voltage bushings requires (a) knowledge about relations between insulation conditions and dielectric quantities (e.g. dissipation at service temperature, polarisation/ depolarisation currents PDC), (b) considering of parasitic currents in the environment of the bushing, (c) knowledge about the dissipation factor at service temperatures which is normally unknown (although possibly high and dangerous) and (d) distinguishing between influences of geometry, oil-conductivity, ageing and moisture on dielectric measurements. A number of solutions will be discussed:
Traditional **off-line diagnosis** of capacitance and dissipation factor at power frequency can be significantly improved by analysis of polarisation and depolarisation currents (PDC) giving information about external influences, moisture, ageing and thermal stability, even at off-line diagnostic temperatures. It is not always correct to relate dielectric measurements to the insulation core of the bushing only, there are parasitic currents from the environment to the grading foils. It was found that measurements with conductive bandages can give lower and upper limits for the diagnostic signals. Therefore it is proposed to improve current signal estimation by a set of measurements. Investigations on oil-impregnated paper samples show that moisture mainly influences conduction currents. Additionally it was found that aged bushings show strongly enhanced polarisation currents in a range of a few seconds. Thereby it was possible to identify strongly aged 400 kV OIP-bushings at room temperature, although there was no indication from dissipation factor measurements. PDC analysis is the first known dielectric method for the identification of aged OIP-insulation at room temperature. Separation of different parameters: It is proposed to distinguish the influences of ageing, moisture and geometry (e.g. barrier systems in transformers) by PDC-analysis: (1) Ageing can be detected from strongly enhanced polarisation currents within some seconds. (2) Conduction currents contain information both about moisture and ageing. (3) External influences have to be

considered by means of conductive bandages.

Usual offline test intervals are by far too long in order to detect progressive failure developments. Permanent **online-monitoring** of relatively cheap bushings is desirable in order to protect expensive and important transformers. Monitoring can make use of basic quantities such as oil-level, pressure and temperature in order to detect dangerous conditions and thermal runaways. Dielectric quantities might be used to detect slow progresses of ageing. Capacitance, losses, partial discharges and fault gases could be monitored to identify critical situations prior to a total breakdown. It will be a challenging task to extract these quantities from the mixed signals out of real online measurements.

1. INTRODUCTION

Dielectric diagnosis of bushings is normally performed by off-line power frequency measurements of capacitance C and dissipation factor tan δ at the measuring tap which is connected to the outermost grading foil, fig. 1. The bushing capacitance is a sensitive quantity for the detection of partial breakdowns between grading foils. Unfortunately it does not give information about ageing 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 usually 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.

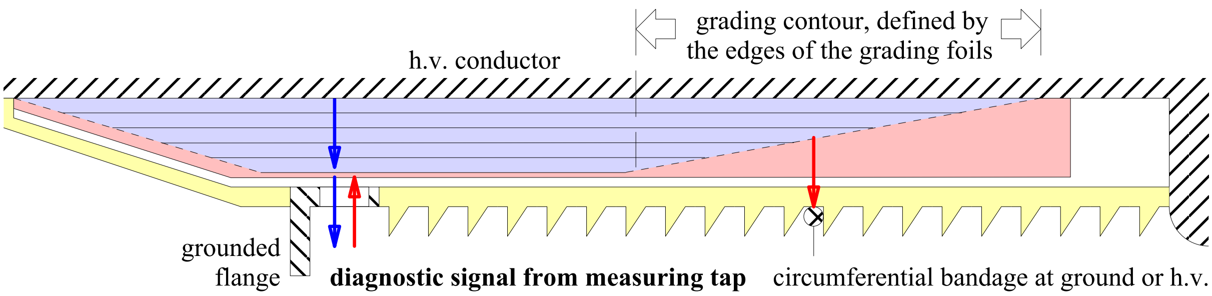


Fig. 1: PDC measurement at the measuring tap of a bushing with a circumferential bandage in the middle of the grading contour, connected either to ground or to diagnostic voltage (h.v.).

2. OFFLINE DIAGNOSIS

2.1 Dielectric Diagnosis

Dielectric measurements can be performed in frequency domain (FDA frequency domain analysis) or in time domain (PDC polarisation and depolarisation currents). For linear systems both methods are mathematically equivalent [1], [2], [3]. The authors decided to use PDC analysis because of the following six reasons: *(a)* PDC measurements give step responses containing the whole system information. *(b)* PDC allows to calculate d.c. conductivities containing information about moisture and ageing [4]. *(c)* Currents at different times are related to different influences [5] (e.g. oil quality, ageing, moisture). *(d)* Time domain signals can be observed easily, explained by physical models (ion movement in oil) and described clearly (ion transit times) [6]. *(e)* PDC analysis has been successfully applied to transformer diagnosis [7], [8], [9]. *(f)* Procedures have been developed to extract relevant information from very short measurements.

2.2 PDC Analysis with Charge Difference Method

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. Thereby an equivalent circuit is generated describing linear material properties both in time and frequency domain [10]. Different time constants $\tau_j = R_jC_j$ 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 approximation of end values 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 [11] [12], fig. 2 (left).

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 three characteristic charge quantites from the integration of measured polarisation and depolarisation currents [12], [13], fig. 2 (right). The first quantity $q_p(t)$ is the *total amount of charge*, flown during a time t. 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. The long term value approaches the amount of charge 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:

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

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. 2 (right). Therefore good approximations of κ can be achieved within short measuring times and noise is filtered by the preceding integration.

2.3 Properties of Oil-impregnated Paper

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.
With respect to real insulations, Kraft paper samples (12 x 100 µm) were dried and impregnated first and wetted afterwards: Samples were supported on a stainless steel helix in a stainless steel vessel, dried and impregnated under vacuum, fig. 3 (left). Afterwards a small amount of water was deposited underneath the paper on the bottom and distributed homogeneously within the sample by heating cycles [6]. Prior to a measure-

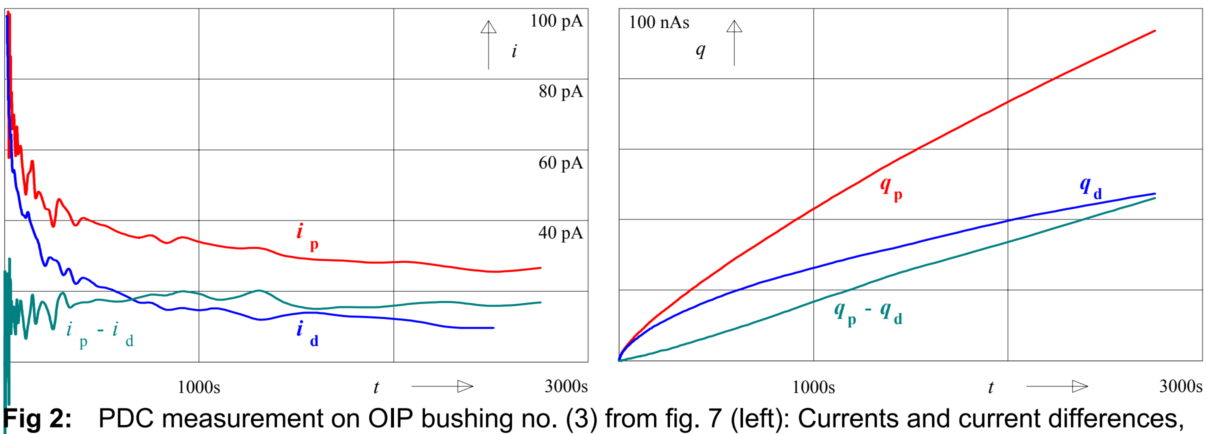


Fig 2: PDC measurement on OIP bushing no. (3) from fig. 7 (left): Currents and current differences, CDM charge difference method (right): Total charge q_p, stored charge q_d and non-stored charge q_p-q_d.

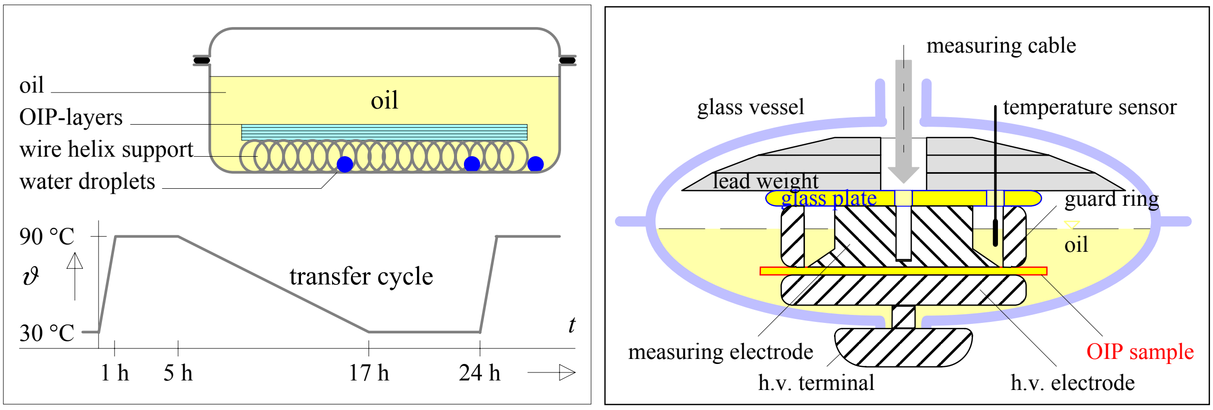


Fig. 3: Defined and uniform wetting of vacuum impregnated OIP samples by moisture transfer (left) and measurement of wetted OIP samples between guard ring electrodes (right).

ment, top and bottom layers were removed in order to check the water content. 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. 3 (right). Investigated parameters were field strength, temperature, water content and oil conductivity, d.c. conductivities were calculated from PDC measurements by the new charge difference method [12]:

There was only a weak dependence on **field strength**, without respect to the high non-linearity of the impregnating oil. Measurements at room temperature, 50 °C and 90 °C showed that **temperature dependence** can be described by an exponential law. I.e. d.c. conductivites at room temperature can be calculated from measurements at elevated temperatures, which gives more accurate results and which allows to normalize conductivities to a reference temperature. By means of the charge difference method CDM different **water contents** can be distinguished very clearly, already within some 100 se-

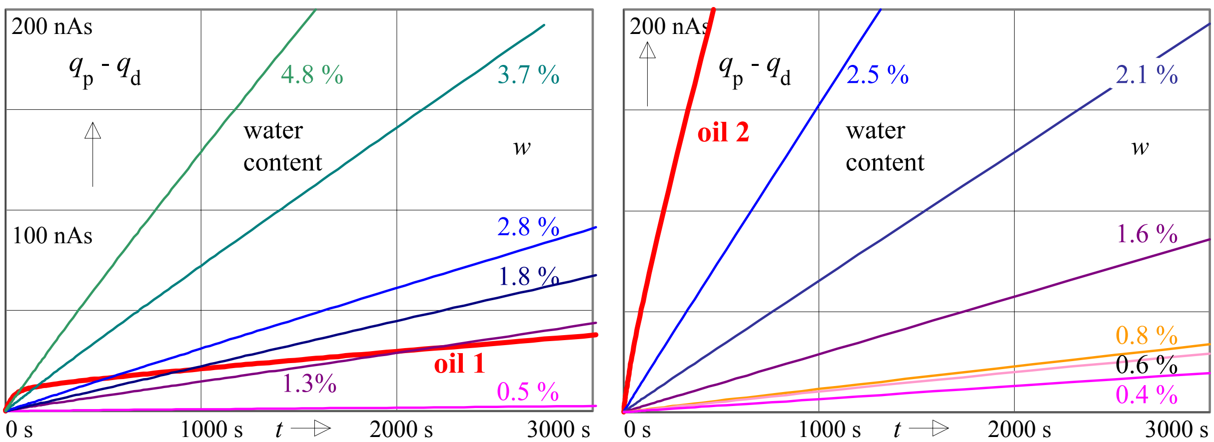


Fig. 4: CDM: *Charge differences* for different water contents *w* in OIP samples, impregnated with a high resistive oil 1 (left) and with a low resistive oil 2 (right) at RT and 0.1 kV/mm. Gradients are proportional to d.c. conductivities of OIP and oil (thin and thick lines).

conds, fig. 4 (left). 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. The OIP conductivity is significantly influenced by the **oil conductivity**. A high resistive oil 1 and a low resistive oil 2 caused significantly different OIP conductivities at the same moisture level, fig. 4 (left and right). I.e. high OIP conductivities can be caused both by water content and by high oil conductivity as it might be generated during ageing processes. Therefore PDC analysis needs further information in order to differentiate the influence of both parameters [14].

2.4 Properties of Aged OIP-Bushings

The properties of aged OIP were investigated on identical service aged 420 kV OIP bushings, fig. 5. According to gas-in-oil analysis no. (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! Obviously the severely aged bushings (1) and (5) can be detected from significantly enhanced polarisation currents within some ten seconds, fig. 5. These currents are caused by additional polarisation processes related to ageing products. Independently from their ageing conditions bushings no. (1) ... (4) are classified by PDC analysis to be “dry” because of low d.c. conductivities [10], [15]. No. (5) has a higher d.c. conductivity which might be related to a water content of 2.4 % [5], [10], but on the other hand it is known that no. (5) is se-

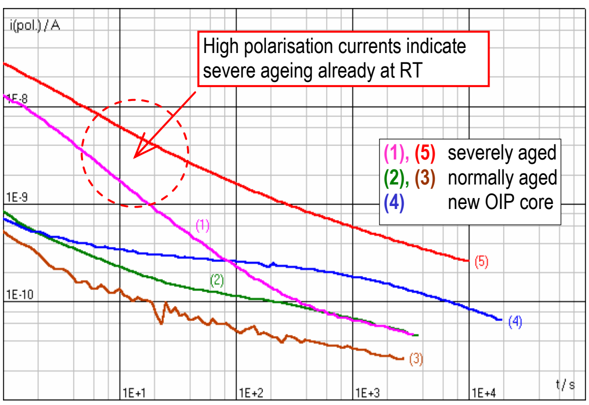


Fig. 5: PDC measurements on identically designed 420 kV OIP bushings, differently aged in service, measurement at RT and 1 kV.

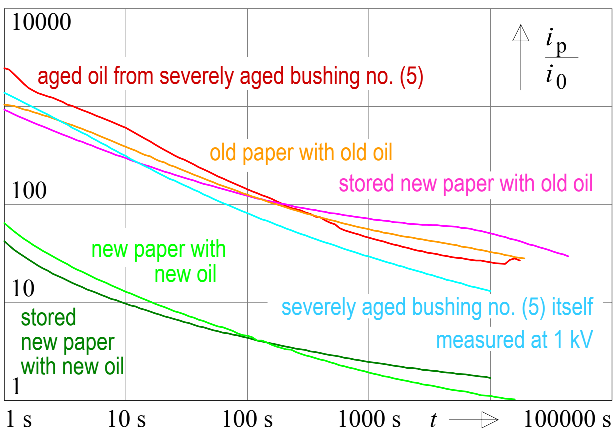


Fig. 6: Influence of service aged oil on polarisation currents in OIP. Currents are normalized to the same capacitance, measured at RT and 1 kV/mm.

verely 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.

It is concluded that PDC analysis can be used to distinguish ageing and enhanced water content of OIP. Severely aged OIP insulations can be detected with PDC measurements already at room temperature, which is not possible with power frequency tan δ measurements!

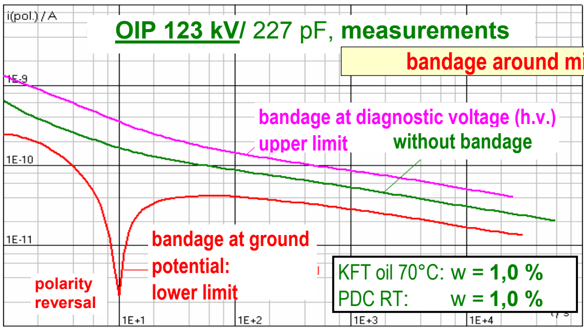
It is supposed that ageing of the OIP insulation system mainly influences the dielectric properties of the oil. This was investigated on samples with different papers impregnated (resp. immersed) in new oil and in aged oil taken from bushing no. (5), fig. 6. If aged oil is used both with new and aged paper, polarisation currents are very similar to currents through aged bushings. If new oil is used, polarisation currents are smaller by one order of magnitude. Obviously ageing products accumulated in the oil have a dominant influence on polarisation currents in OIP.

2.5 External Influences

In chapter 2.4 it is assumed that dielectric measurements can directly be related to the bushing core. This is not always true: Leakage currents from grading foils to ground can be responsible for "negative dissipation factors" [16] and for polarity reversals during PDC measurements. Therefore it was investigated under which conditions correct dielectric measurements on bushing are possible.

In order to explain the effect, a conductive path is assumed from ground or h.v. to the free ends of the grading foils, fig. 1. In frequency domain its influence can be described by a phase shift between measured current and applied voltage *U* which can be bigger or smaller than 90°. Thereby the dissipation factor appears to be negative or positive. Notice: It is an *apparent* effect, in reality an ideal capacitance does neither produce nor dissipate energy [17].In time domain the influence of the conductive path can be described analogously by a reduction or an enhancement of the measured current at the potential tap, fig. 1. A conductive path to ground can result in a temporary discharging of bushing capacitances, in a negative current and in two polarity reversals [12].

These effects were investigated by a set of three PDC measurements, fig. 7: *(1)* A 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 a bandage at diagnostic voltage (h.v.). Measurement (1) gives an estimation of the



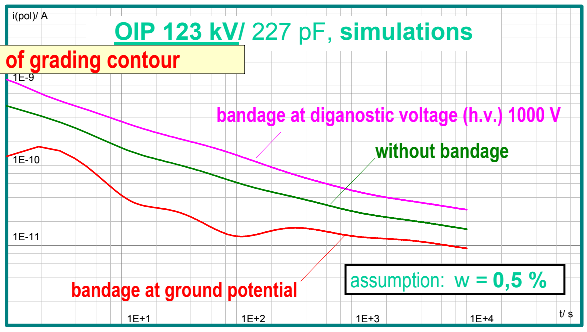
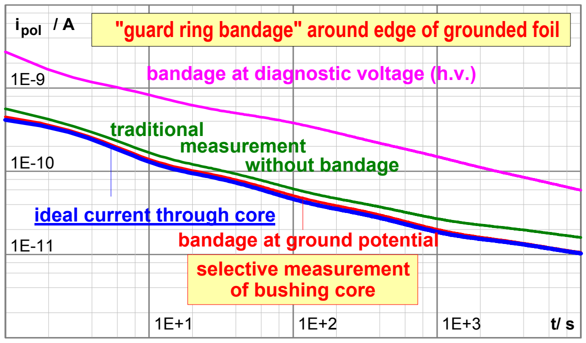


Fig. 7: PDC measurements without and with bandages in the middle of the grading contour. Bandages at h.v. and ground give upper and lower limits for polarisation currents through the bushing's core (**worst case bandages**), measurements (*top left*) and simulations (*top right*).

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*).



current through the bushing's 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. 7 (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 [17]. Every element consisted of capacitance (replacing permittivity), resistance (replacing conductivity) and *RC*-elements (replacing different polarisation processes). These equivalent circuits, describing the local materials, were 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. 7 (top right and left). Therefore the simulation model 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 measuring tap is therefore identical with the current through the bushing's core, fig. 7 (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].

These results can be applied to offline measurements on bushings in the following way: 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. 7 (top). In the case of severely aged bushings, currents are strongly enhanced and leakage currents are negligible. The upper and lower limits are close together and the traditional measurement without bandages is considered to be correct.

3. ONLINE MONITORING

3.1 Significance and Measurement of *C* and tan δ

The traditional offline diagnosis has two disadvantages: Measurements are taken in very long time intervals which are definitely too long for detection of a progressive failure development. Furthermore conclusions are indirect, especially dissipation factor tan δ at service temperature cannot be measured directly. Therefore permanent supervision resp. online monitoring of capacitance *C* and dissipation factor tan δ at service temperature is most desireable. These quantities contain valuable information: Partial breakdowns, which require immediate action, can be detected from changes of capacity just in the moment of the partial breakdown event. 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. Online monitorining gives a permant picture of the situation.

Traditionally *C* and tan δ are measured in special bridge circuits (e.g. Schering brigde), containing the bushing to be measured and a reference capacitor with well known and stable properties. Manual or automatical balancing of the bridge provides very accurate results, but a bridge is too complex for a online monitoring system. Alternatively, signals taken from the bushing's measuring or potential tap and from a reference path can be compared continuously. Two main questions have to be answered:

1.) How is it possible to get a reference signal which is independent of the bushing?

2.) How are the signals to be processed in order to overcome the influences of noise, harmonics, voltage fluctuations and asymmetries?

3.2 Generation of Reference Signals

Reference signals can be generated in different ways. Some principles and problems are listed below:

Principle, method		Problems
1.	External reference capacitor.	Extremely expensive, not realistic.
2.	External signal from a voltage transformer or divider.	Signal transmission is required.
3.	Cyclic replacement of load impedances at the potential tap [18].	Voltage fluctuations disturb measurements.
4.	Summation of three signals in a three phase system [19].	Synchroneous ageing is not detected. Phase imbalances disturb interpretation.
5.	Comparison of different signals against each other.	
6.	External signal from an additional bandage [20] resp. electrode [21] in a single phase system.	Sensitive to neighbour phases, sensitive to changes in the environment, distortion of the electric field.
7.	Use of existing coupling capacitances in single-phase or multi-phase systems without field distortion [22].	Sensitive to changes in the environment.

Because of the various drawbacks, method no. 7 was applied. The use of existing stray and air capacitances as coupling capacitances is common practice for measuring of voltages and fields, e.g. for electrostatic voltmeters or capacitive probes [22]. In order to avoid triggering of flashovers it is important not to disturb a given field geometry, fig. 8.

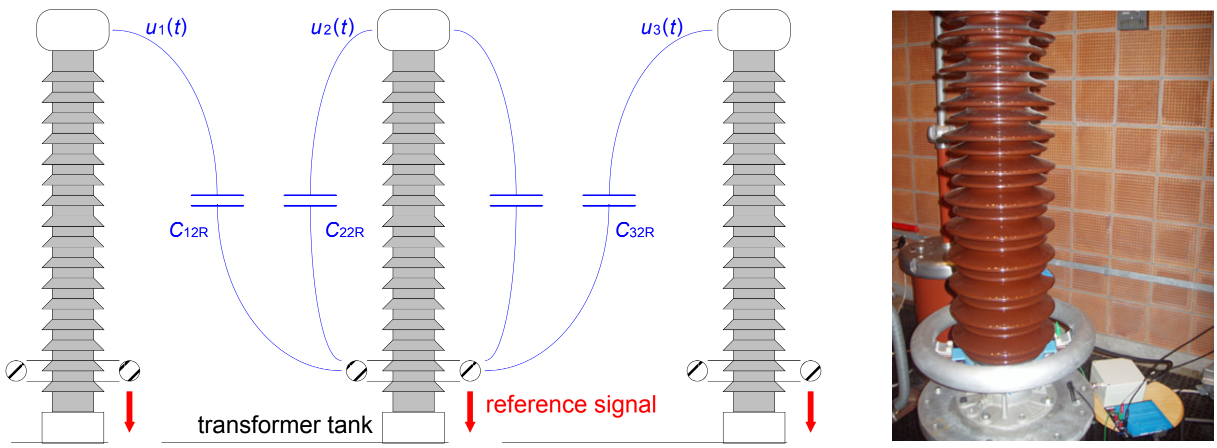


Fig. 8: Generation of reference signals by use of existing coupling capacities in a multi-phase system.

3.3 Signal Processing

The signals which shall be compared are fed into a PC through an A/D-converter and are further processed digitally. In this step it is important to filter the digital input data for phase difference measurements, in order to exclude harmonics and to be able to process the pure power frequency signal afterwards. In the further analysis the phase difference is determined digitally and treated with different mathematical operations, e.g. by averaging. Due to the availability of digital data, discrete fourier transformation (FFT) algorithms can be used to transform signals from time to frequency domain. In frequency domain the quantities 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, fig. 9.

3.4 Results

The described monitoring system was tested with oil impregnated paper samples with a high water content. The samples consisted of eight layers which were measured between guard ring electrodes. The signal was measured across a low voltage capacitance of 33 nF. The reference signal was measured at a potential free toroid which was coupled to the high voltage side by air resp. stray capacitances. In order to examine the function of the system, the measured dissipation factor tan δ was compared to the results from a conventional Schering bridge measurement.

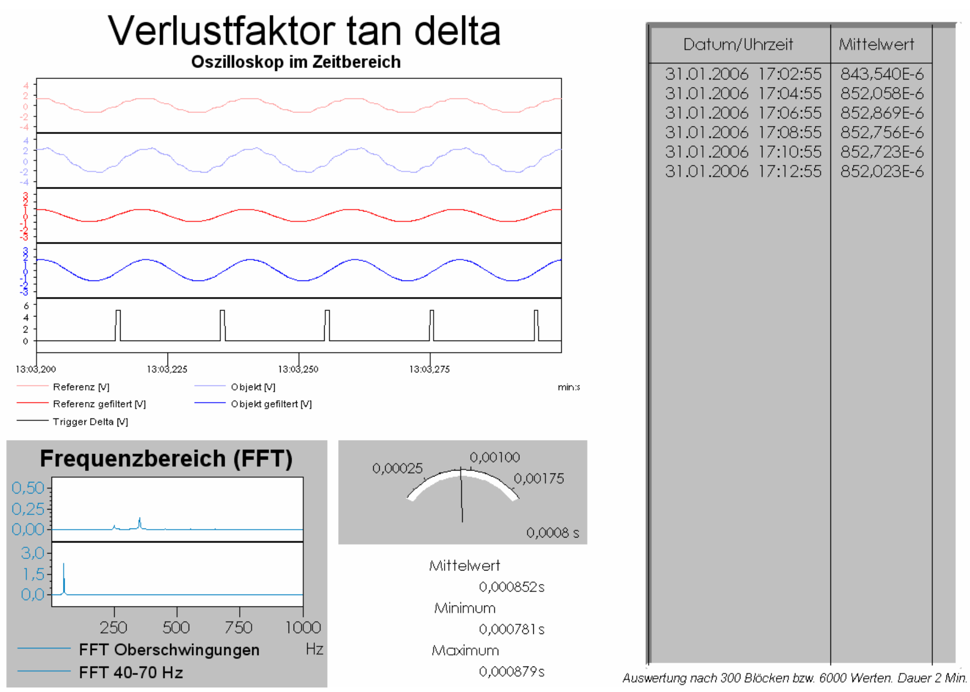


Fig. 9:
Signal processing for online dissipation factor monitoring.

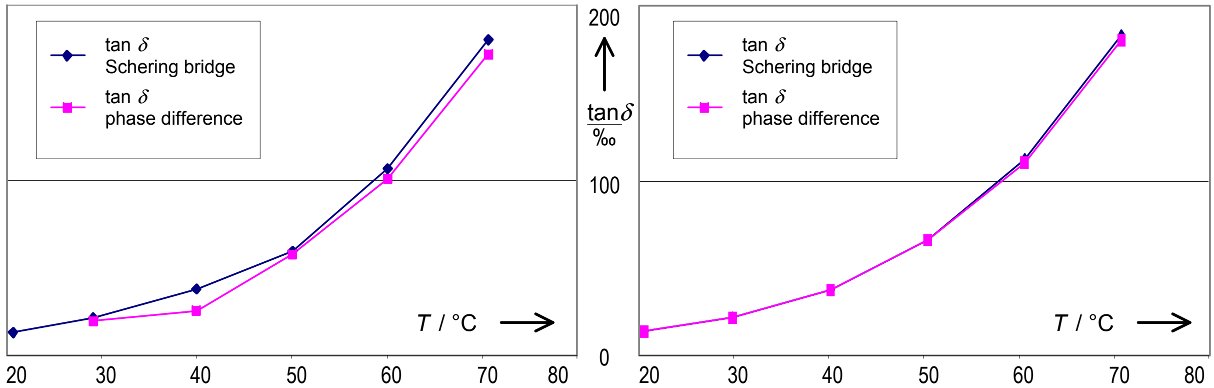


Fig. 10: Improvement of online dissipation factor monitoring by means of improved statistical signal processing.

For the estimation of the sensitivity of the system the tempearature of the sample was increased similar to service temperatures in the core of a bushing. Thereby the dissipation factor increased dramatically due to the poor quality of the wetted sample. Results from the online monitoring system are in good agreement with the off-line Schering bridge measurements. Up to now several steps of signal processing improvements could be achieved, fig. 10. The here monitored dissipation factor values for the significantly wetted OIP sample would indicate a high danger for the thermal instability of a real bushing, but it would have been clearly recognized however by the here described online monitoring system.

Several sucessful tests with real 110 kV bushings already show that the monitoring system can be used in a three phase voltage system as well. The reference signals are taken from coupling capacities to all AC phases, fig. 8.

4. CONCLUSIONS

(1) The *PDC analysis* is a powerful tool for the offline diagnosis of bushings especially with OIP oil impregnated paper insulation. It can be further improved by the *charge difference method CDM* which is insensitive to noise and gives quick estimations for d.c. conductivities.

(2) Dielectric properties of OIP samples were investigated with PDC measurements 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 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 causes high values of polarisation currents in an early phase during some hundred seconds after beginning of polarisation. Thereby severely aged bushings 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.

(4) Advanced *online monitoring* systems are able to monitor dielectric quantities *C* and tan δ at power frequency, service voltage and service conditions. The measured quantities give direct information about partial breakdowns and thermal stability. Even under service conditions there are several options for getting reference signals and for effective signal processing.

Acknowledgement:

The authors gratefully acknowledge the financial support of this work by DFG Deutsche Forschungsgemeinschaft (KU 1384/3-1 and -2) and BMBF Bundesministerium für Bildung und Forschung (17 45A 04) concerning chapter 2 and 3 resp.. Valuable discussions about properties and processing of OIP samples were performed with Christoph Krause from Weidmann Transformerboard AG, Rapperswil. The authors also want to express many thanks to Dr. Norbert Koch for very important contributions to our work and to Elena Kern, Georg Schaller, Heiko Roisch, Michael Seubert and Franz Klauer for significant support.

References:

[1] W.S. Zaengl; “Dielectric Spectroscopy in Time and Frequency Domain for HV Power Equipment”; ISH Int. Symp. on High Voltage Engineering, 2001, Bangalore India

[2] S.M. Gubanski, P. Boss, G. Csépes, V. Der Houhanessian, J. Filippini, P. Guuinic, U. Gäfvert, V. Karius, J. Lapworth, G. Urbani, P. Werelius, W. Zaengl; “Dielectric Response Methods for Diagnostics of Power Transformers”; CIGRÉ TF 15.01.09, Electra No. 202, June 2002

[3] T.K. Saha, P. Purkait; “ Investigation of Polarization and Depolarization Current Measurements for the Assessment of Oil-paper Insulation of Aged Transformers”; IEEE Transact. on Dielectrics and El. Insulation, Vol. 11, No.1; February 2004, pp. 144-154

[4] A. Küchler, T. Bedel; “Dielectric Diagnosis of Water Content in Transformer Insulation Systems”; ETEP European Transactions on Electrical Power, Vol. 11, No. 1, 2001

[5] V. Der Houhanessian; “Measurement and Analysis of Dielectric Response in Oil-Paper Insulation Systems”; PhD Thesis, ETH Zuerich, Switzerland 1998

[6] A. Küchler, F. Hüllmandel, J. Hoppe, D. Jahnel, C. Krause, U. Piovan, N. Koch; “Impact of Dielectric Material Responses on the Performance of HVDC power transformer insulations”; 13th ISH Int. Symp. on High Voltage Engineering, Delft 2003

[7] A. Kachler, T. Leibfried, A. Küchler, B. Breitenbauch, W.S. Zaengl, V. Der Houhanessian; “Ageing and moisture analysis of power transformer insulation systems”; 12-101, CIGRÉ 2002 session, paper 12-101, Paris 2002

[8] B. Breitenbauch, A. Küchler, T. Leibfried, W.S. Zaengl; “Insulation Diagnosis by Polarization and Depolarization Current Measurements”; 13th ISH Int. Symp. on High Voltage Engineering, Delft 2003

[9] S.A. Bhumiwat, P. Stattmann; “Quality Assurance after Transformer Refurbishment by means of Polarisation Depolarisation Current Analysis”; IEEE-BPT03, Bologna, Italy, 2003

[10] J.-J. Alff, V. Der Houhanessian, W.S. Zaengl, A.J. Kachler; “A Novel, Compact Instrument for the Measurement and Evaluation of Relaxation Currents Conceived for On-Site Diagnosis on Electric Power Apparatus”; IEEE Symposium on El. Insulation, Anaheim, USA, 2000

[11] A. Küchler; “Hochspannungstechnik”; Springer Press, Berlin-New York, 2nd edition 2005

[12] A. Küchler, F. Hüllmandel, K. Böhm, C. Neumann, N. Koch, K. Loppach, C. Krause, J.J. Alff; “Condition Assessment of Aged Transformer Bushing Insulations”; CIGRÉ Session 2006, Paris 2006

[13] K. Böhm; “Dielektrische Diagnose von Hochspannungsisolierungen”; Master thesis, FHWS Schweinfurt, 2005

[14] Z.T. Yao; “Analysis and Modelling of Dielectric Response in Power Transformer Insulation”; PhD thesis, University of Queensland, Australia, 2003

[15] A. Küchler, F. Hüllmandel, K. Böhm, N. Koch, P. Brupbacher, C. Krause; “Das dielektrische Verhalten von Öl-Papier-Isolationen unter der Wirkung von Grenzflächen-, Material- und Prüfparametern”; ETG-Conf. “Grenzflächen in elektrischen Isoliersystemen”, Hanau, 2005

[16] L. Pong; “Review Negative Power Factor Test Results and Case Study Analysis”; The 2002 Int. Conference of Doble Clients; Boston/ USA, 2002

[17] A. Küchler, F. Hüllmandel, K. Böhm, N. Koch; “Einfluss äußerer Grenzflächen auf die dielektrische Diagnose betriebsgealterter Hochspannungsdurchführungen”; ETG Conf. “Grenzflächen in elektrischen Isoliersystemen”, Hanau, 2005

[18] N. Koch; "Low-cost monitoring von Durchführungen"; HSP-Kolloquium, 30/31. Oktober 2000

[19] M.Y. Lau, T. Schwartz, D.E. Bates, C.F. Kane, A.A.Golubev, A.B. Seliber, V.A. Rusov, S.V. Zhivodernikov; „On Line Monitoring Systems for Bushings“; Doble Engineering Company 2004

[20] A. Küchler, F. Hüllmandel, K. Böhm, N. Koch; “Einfluss äußerer Grenzflächen auf die dielektrische Diagnose betriebsgealterter Hochspannungsdurchführungen”; ETG Conf. “Grenzflächen in elektrischen Isoliersystemen”, Hanau, 2005

[21] A. Setayeshmehr, A. Akbari, H. Borsi, E. Gockenbach; “On-line Monitoring of Power Factor (tan δ) and Capacitance of Transformer Bushings”; XIVth International Symposium on High Voltage Engineering, Beijing, China 2005

[22] A. Küchler; „Erfassung transienter elektromagnetischer Feldverteilungen mit konzentrierten und räumlich ausgedehnten Sensoren“; PhD thesis, Univ. Karlsruhe, VDI-Verlag, 1986

Authors:

Prof. Dr.-Ing. Andreas Kuechler
Dipl.-Ing. (FH) Frank Huellmandel
M.Eng. Konrad Boehm
Dipl.-Ing. (FH) Marcus Liebschner
Dipl.-Ing. (FH) Manuel Appold

[1)]FHWS University of Applied Sciences
Fachhochschule Würzburg-Schweinfurt
Ignaz-Schön-Str. 11, 97421 Schweinfurt

Phone: ++49 (9721) 940-840
Fax: ++49 (9721) 940-800
E-mail: akuechler@fh-sw.de

Dr.-Ing. Reiner Krump
Dipl.-Ing. Joachim Titze

[2)]HSP Hochspannungsgeräte Porz GmbH
Kaiserstr. 127
51145 Köln

Phone: ++49 (2203) 3005-60
Fax: ++49 (2203) 9252-60
Email: reiner.krump@hspkoeln.de