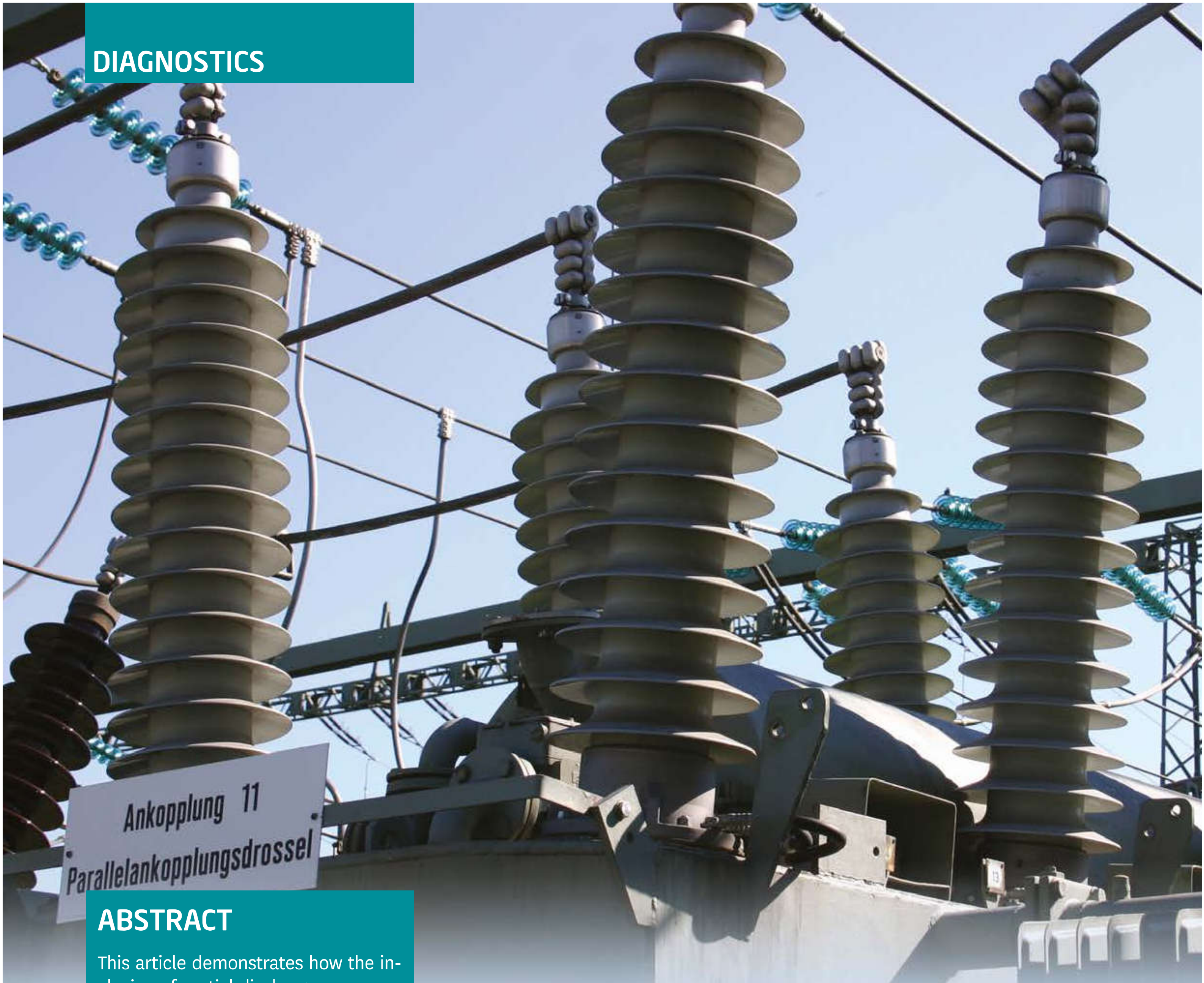


Effective bushing diagnosis using partial discharge testing

Partial discharge measurements effectively detect failure-causing defects

ABSTRACT

This article demonstrates how the inclusion of partial discharge as a measurement parameter ensures a more reliable diagnosis of insulation condition in transformer bushings. Comparative diagnostic tests showed that the partial discharge measurements best enabled the detection of bushing defects, which the other methods were not able to detect alone.
The tests were performed in the lab on oil-impregnated paper (110 kV – with induced defects) and resin-bonded paper (52 kV – with design flaws) bushings. The bushings were subjected to long-term AC tests during which the capacitance, dissipation factor and partial discharge levels were continuously measured. A correlation between the measured parameters and the bushing condition was performed to reach a best-practice conclusion.

KEYWORDS

bushing, insulation system, partial discharge measurement

1. Introduction

CIGRE recently published a technical brochure in which 964 major transformer failures occurring between 1950 and 2009 were analysed [1]. Transmission and distribution transformers, as well as shunt reactors and generator step-up transformers (GSU), were considered in this analysis. Their overall failure rate was within

1 %. Dielectric failures were the most significant in all transformer classes [1]. The windings, bushings and lead exits are affected by this failure mode. It is known that bushings are responsible for approximately 14 % of major transformer failures regardless the type of their insulation system – resin-bounded paper (RBP), resin-impregnated paper (RIP) or oil-impregnated paper (OIP) [1]. The failure rate is even higher, approximately 18 %, when the analysis is limited to transformers manufactured after 1980, Fig. 1.

Based on field experience, a bushing manufacturer attributes oil leakages (80 %), insulation deterioration (13 %) and mechanical damages (7 %) as the main root causes of bushing failures [2]. The first two failure causes are directly related to the ageing process of the insulation, which is influenced by high temperatures, load cycles, transient over-voltages, moisture ingress and cracks. The early identification of these defects can be shown by the bushing's most important diagnosis factors: dissipation factor (DF), capacitance (C) and partial discharge (PD) level [3]. However, in many cases the individual evaluation of these parameters cannot reveal defects in the incipient stage. This is why this article focuses on bushing diagnosis by considering the simultaneous information coming from DF, C and PD measurements.

2. Detection of bushing defects

2.1 Capacitance and dissipation factor

One way to analyse the bushing condition is to check the DF value and its rate of change over time. When the DF reaches a predefined level, Table 1 [4], the continuous operation of the bushing is no longer recommended. The diagnosis of bushings based on their C is done by comparing the values from the last measurement with the nameplate value. The difference between them gives the capacitance variation (ΔC), which has to remain within certain limits depending on the bushing rated voltage and number of grading layers. The change of bushing capacitance when one insulation layer is short-circuited is presented for bushings of different rated voltages in Table 2 [5]. If the number of the grading layers is unknown, the value of the insulation dielectric strength helps to estimate the number of the bushing layers and to set adequate threshold limits for the capacitance variation. According to reference [6], the bushings are designed to operate under electrical fields that do not exceed 2 kV/mm for RBP, 3.6 kV/mm for RIP and 4.5 kV/mm for OIP insulation. The distance between two consecutive grading layers could be about 2 mm (it depends as well on the bushing rated voltage and bushing manufacturers).

> **Bushings are responsible for approximately 14 % of major transformer failures regardless the type of their insulation system**

> **The rate of transformer failures caused by bushings is even higher, approximately 18 %, when the analysis is limited to transformers manufactured after 1980**

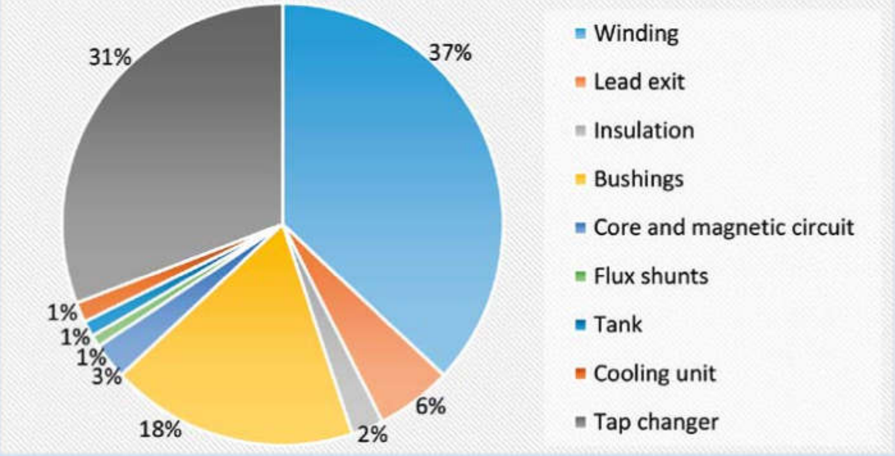


Figure 1. Failure location in transformers manufactured after 1980 (342 failures, U ≥100 kV) [1]

Table 1. Acceptance level of dielectric losses for bushings of different design (at 20 °C) [4]

Standards	RIP	OIP	RBP
DF **IEC 60137**	<0.7 %	<0.7 %	<1.5 %
PF **IEEE C57.19.01**	<0.85 %	<0.5 %	<2 %

Table 2. Voltage class and change of capacitance for condenser type bushings [5]

Voltage in kV	No. of layers	Change in %
123	14	7.1
245	30	3.3
420	40	2.5

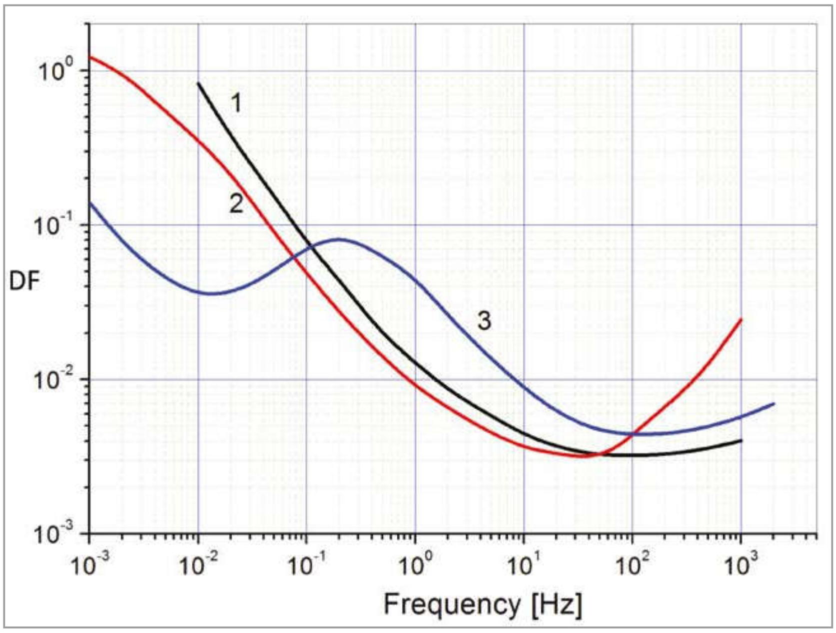


Figure 2. DF measurements on: healthy bushing (1), ungrounded tap for 3h (2), tap grounded 50 h AC test (3)

> **Inclusion of partial discharge as a measurement parameter ensures a more reliable diagnosis of insulation condition in transformer bushings**

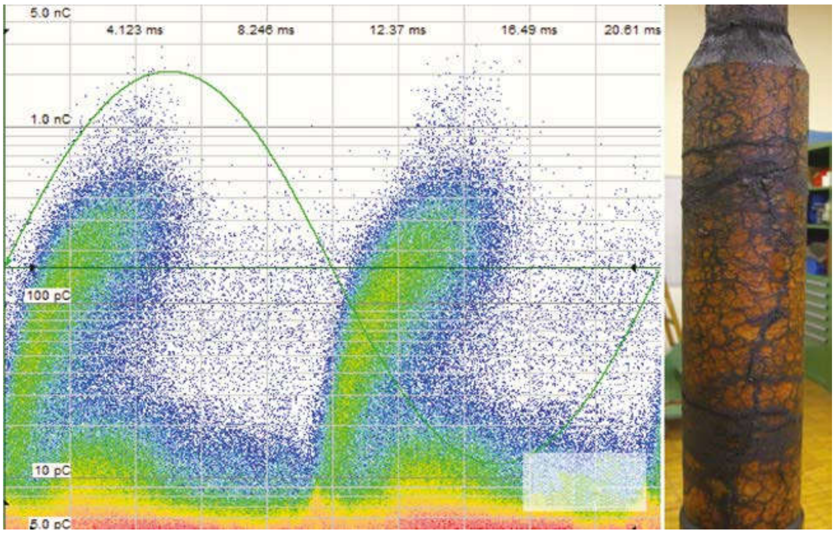


Figure 3. Example of PRPD pattern of defective RBP bushing (discharges of the surface of the bushing insulation)

Off-line C and DF measurements can be performed in a wide frequency range to identify the presence of defects, such as shorted grading layers; contact problems and high impedance faults between layers or at the test tap; insulation ageing; as well as contamination and moisture ingress. As an example, the results of such measurements performed on an OIP bushing with a damaged test tap are shown in Fig. 2.

The bushing was in operation for three hours with an ungrounded measuring tap. This led to a voltage potential of about 15 kV between the tap and flange (calculated after opening the bushing based on the insulation thickness and the recommended electrical field distribution inside the bushing). These triggered electrical discharges resulting in the bushing tap damage. The results of the DF measurements performed on the defected bushing (curve 2) were compared to the ones obtained on the healthy bushing from another phase of the same transformer (curve 1). Curve 3 was obtained after the same defected bushing was subjected to the operating voltage (grounded tap) in the lab for 50 hours.

Two types of polarization processes (interface and orientation) were noted in the defective bushing, Fig. 2, curve 2. At frequencies above 100 Hz, the migration of the by-products resulting from oil and paper decomposition (e.g. acids, water, hydrocarbons and even solid particles) increased the DF value. The relaxation at frequencies below 0.01 Hz could be the result of the presence of a small amount of gas. When the bushing with the damaged but grounded measuring tap was tested at the operation voltage for 50 hours, Fig. 2, curve 3, the electrical field triggered the interface polarization and the separation of the by-products at the insulation oil-paper interfaces. This lead to an increase of electrical conductivity between the insulation layers and to a higher DF value.

OIP and RIP bushings that have passed the routine test are either PD-free or the PD level does not exceed the acceptable level of 10 pC specified in the IEC 60137 standard

2.2 Partial discharges measurement on bushings

PD is measured on bushings using a set-up typically used for factory acceptance tests [7]. In general, OIP and RIP bushings that have passed the routine test are either PD-free or the PD level does not exceed the acceptable level of 10 pC specified in the IEC 60137 standard [8]. This happens due to the manufacturing technology that ensures the entire removal of the air bubbles from the insulation (mix of resin or oil and paper). As the insulation in RBP bushings is a laminate of resin and paper, the bushing contains a considerable amount of air distributed in the insulation and especially at the edges of the grading layers. This is why even new RBP bushings that may show a PD level of around 100 pC could pass such a routine test. The equipment used for the PD tests presented in this paper is a synchronous, three-channel system, whose digital bandpass filter (bandwidth from 9 kHz to 5 MHz) can be freely set for measurements up to 35 MHz. The PD results are visualized as phase-resolved PD (PRPD) patterns, which give the correlation between the PD pulse occurrence time and the applied voltage phase. Different types of defects generate patterns of different shapes [9]. Both apparent charge magnitude and PD pulse repetition rate need to be indicated in order to get complete information about the defect type. An example of such a PRPD pattern is presented in Fig. 3. The PRPD pattern presented here was obtained while performing PD measurements on a 220 kV RBP bushing affected by surface discharge as a result of moisture ingress.

3. Test set-up and tests performed

The set-up for the PD measurements carried out in the lab is presented in Fig. 4. Two bushings of different insulation systems and rated voltages were tested:

Table 3. Bushing defects and parameters measured

Bushing	Tests	Parameters
OIP	Oil dried and degassed	C, PD
	Oil contamination with atmospheric air and transformer sludge	
	Reduction of oil level by half	
RBP	Technological defects	C, DF, PD

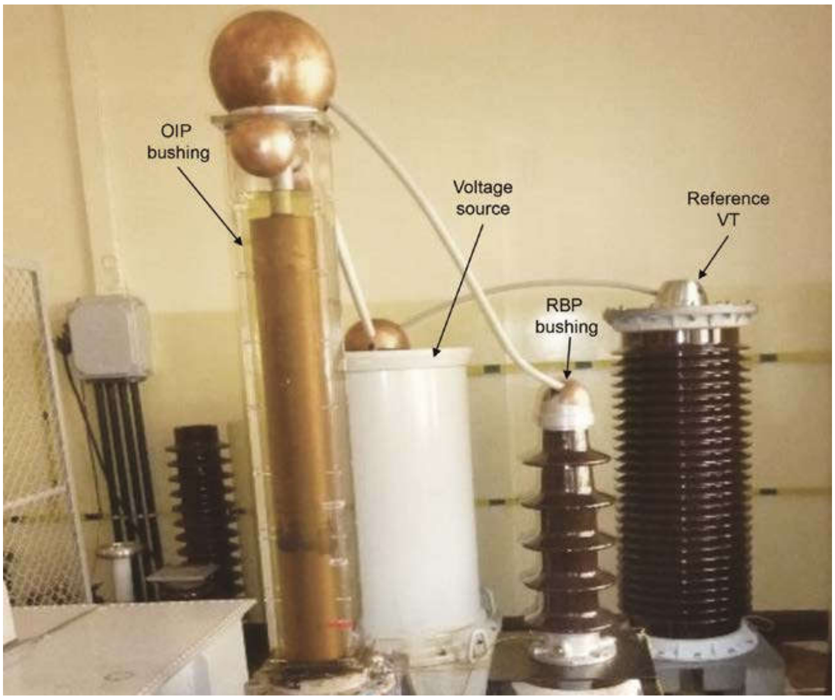


Figure 4. Test set-up for OIP and RBP bushings insulation evaluation

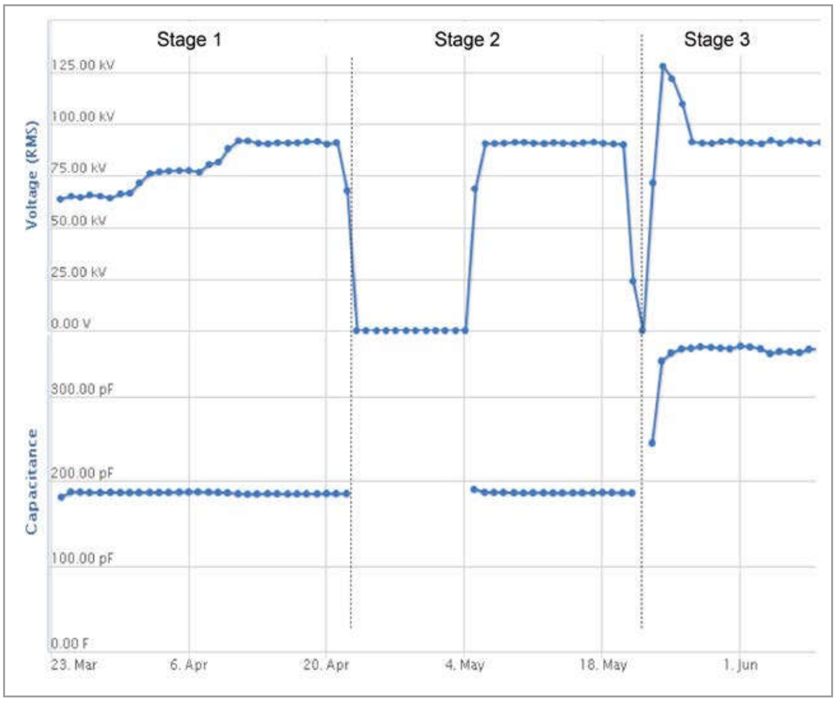


Figure 5. Test voltage and capacitance during the testing period

> **The insulation in RBP bushings contains a considerable amount of air, so even new RBP bushings that may show a PD level of around 100 pC could pass routine tests**

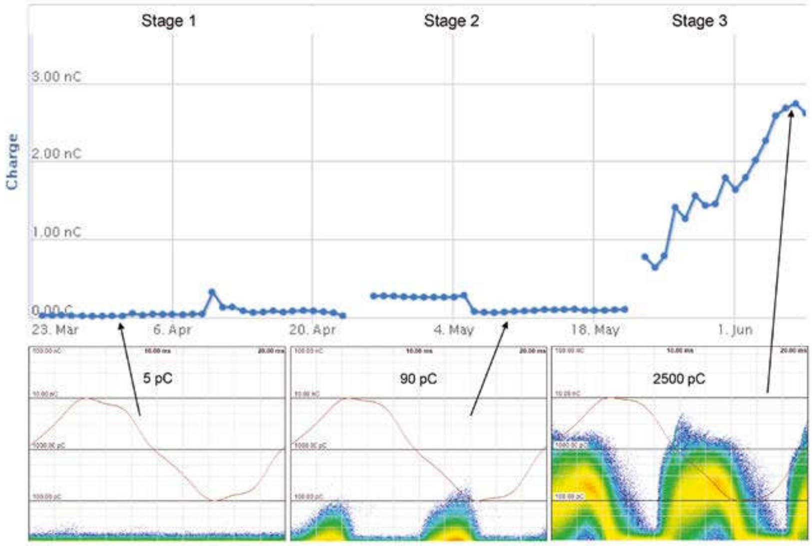


Figure 6. PD trend and PRPD patterns during OIP bushing testing

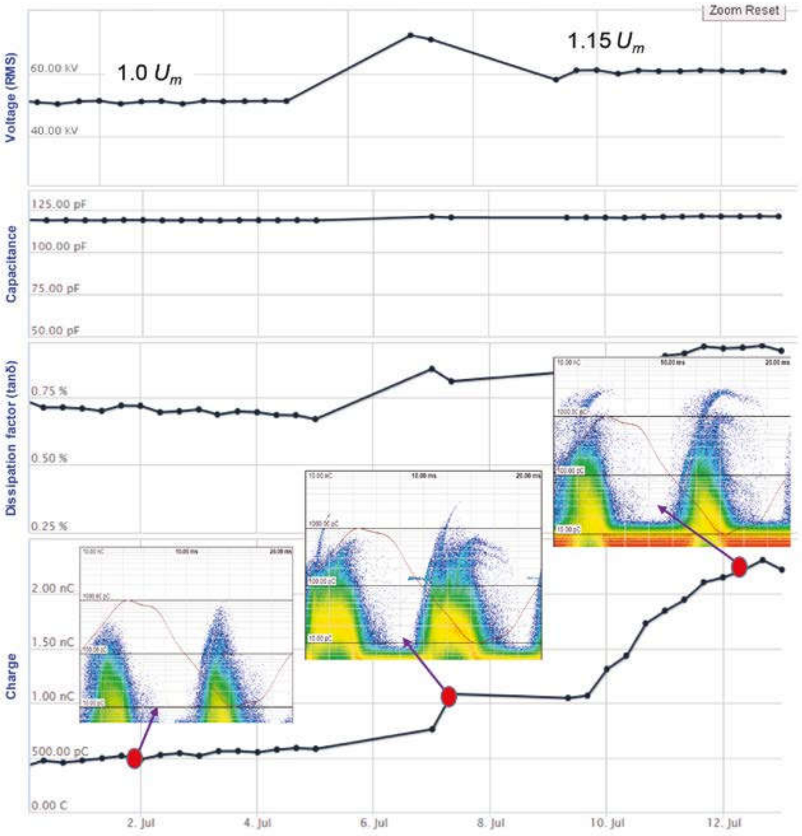


Figure 7. C, DF and PD variation for RBP bushing

- A 110 kV, 24-year-old OIP bushing: the porcelain cover was removed in order to simulate different condition defects and to observe the insulation behaviour under electrical stress (bubbling, surface discharge). The removal of the porcelain cover has a quantitative influence on the bushing capacitance (the new capacitance is regarded as "good" condition capacitance).
- A 52 kV new RBP bushing with design flaws

A voltage transformer (VT) of high accuracy class (0.2) was used, providing a highly stable reference signal for the bushings' DF calculation (the VT fulfilled the role of the reference capacitor).

Due to the high difference between their rated voltages, the bushings were tested in sequence. The PD system was separately calibrated for a wide frequency range on each bushing before initializing the measurements. The bushings' behaviour under relevant defect conditions was investigated by carrying out on-line and off-line measurements of the parameters indicated in Table 3.

4. Results

4.1 Oil-impregnated paper bushing

According to IEC60137 [8], the C testing procedure was performed at the voltage value of $1.05 \cdot U_\mathrm{m}/\sqrt{3}$ (88 kV). The PD testing was performed according to IEC 60270 [7] and the measuring sensitivity was 8 pC. The porcelain cover of the bushing under test was removed before the measurement was performed. The active part of the bushing was then placed into a plexiglass enclosure filled with the same amount (approx. 40 litres) of mineral oil that normally exists in this type of bushing. PD and C were measured for this bushing in the following stages:

- Stage 1: Oil dried and degassed under vacuum in the lab prior the measurement
- Stage 2: Oil contamination with air and sludge
- Stage 3: Oil leakage by removing half of the oil

At Stage 1, the test voltage was gradually increased from $0.75 \cdot U_\mathrm{m}/\sqrt{3}$ to $1.05 \cdot U_\mathrm{m}/\sqrt{3}$, Fig. 5, upper trend. The C value was constant, about 190 pF, Fig. 5, lower trend.

Regardless of the test voltage level, no PD signal was detected, Fig. 6. The voltage at Stage 2 was constant and equal to $1.05 \cdot U_m/\sqrt{3}$ (88 kV) and the bushing capacitance remained stable throughout the test. During the PD measurements, defect-specific PRPD patterns were detected. These were probably the result of discharges in the air bubbles, Fig. 5, middle PRPD, that were artificially introduced. Therefore, it can be concluded that the insulation contamination in the OIP bushings could be detected based on PD.

In Stage 3, an oil leakage was simulated by partly removing the oil from the bushing enclosure. The test voltage remained constant (88 kV). In this case, an increase in the bushing capacitance from 190 pF to 350 pF was recorded. The capacitance increase can be explained based on the parallel capacitances introduced after oil removal. The amount of paper left above the oil gets contaminated with the moisture from the surrounding air. Thus a capacitor of higher capacitance was created having the (wet) paper as a dielectric. The dielectric constant of the (wet) paper ε_r is one of the factors that lead to the capacitance increase.

A significant increase in PD levels after reducing the bushing oil level was noticed as well, Fig. 6, Stage 3. This can be seen by analysing both the PD trend and the corresponding PRPD patterns. However, by comparing the PRPDs from Stages 2 and 3, the presence of two different types of defects can be seen. In conclusion, any oil leakage that may occur during the operation of OIP bushings can be detected based on both C and PD measurements.

4.2 Resin-bonded paper bushing

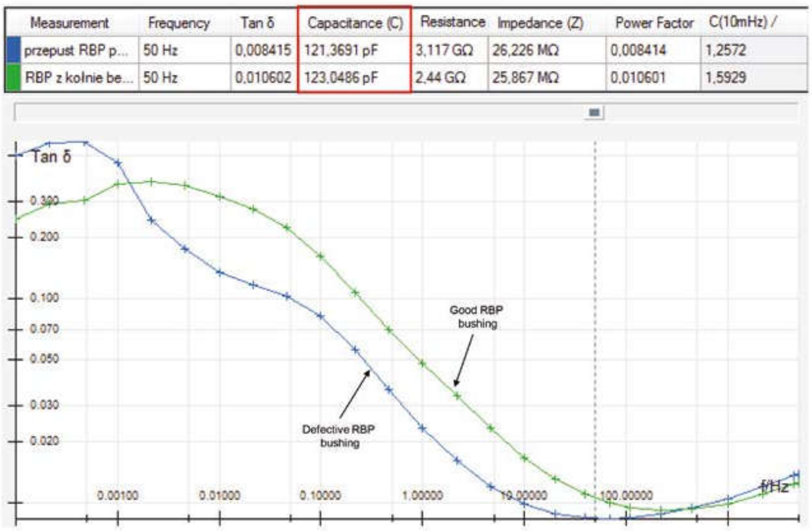
A 52 kV RBP bushing with design flaws was investigated (the bushing failed at the factory acceptance test). According to reference [8], the PD test is passed if the PD level does not exceed the value of 300 pC while testing the bushing at voltages between the 1.05 and $1.5 \cdot U_m$. The bushing being presented here showed a PD level of 500 pC at U_m (caused by the design flaws).

Different types of defects generate different shapes of phase-resolved PD patterns

Any oil leakage that may occur during the operation of OIP bushings can be detected based on both C and PD measurements

During the C, DF and PD tests in the laboratory, the test voltage took values between $1.0 \cdot U_m$ (52 kV) and $1.15 \cdot U_m$ (60 kV) throughout the investigation. At $1.0 \cdot U_m$, both C and DF show stable values, Fig. 7, upper trends, while the PD level increases with a low slope, Fig. 7, lower trend. After increasing the test voltage to the value of $1.15 \cdot U_m$, a steeper increase of the DF and PD values can be observed. The bushing C remains constant as no short circuit of the grading layers occurred. The evolution of the PRPD patterns characteristic to discharges in gas cavities of the insulation is presented in Fig. 7 as well. It can be noticed that the amplitude and the repetition rate of the PD pulses continuously increase.

Off-line measurements of C and DF were performed in a wide frequency range on this RBP bushing as well, Fig. 8. The results obtained here are very close to those obtained from on-line testing at $1.0 \cdot U_m$. The voltage level applied for the off-line tests was 100 V and therefore too low in order to trigger the PD activity in the existing gas cavities. At the next step, the bushing was opened for a detailed investigation and several traces of PD activity were found, Fig. 9. Most of the carbonized areas were located in the region of the flange. Only few insulation punctures were found near the ends of this RBP bushing.



	Measurement	Frequency	Tan δ	Capacitance (C)	Resistance	Impedance (Z)	Power Factor	C(10mHz) /
🟦	przepust RBP p...	50 Hz	0,008415	121,3691 pF	3,117 GΩ	26,226 MΩ	0,008414	1,2572
🟩	RBP z kolnie be...	50 Hz	0,010602	123,0486 pF	2,44 GΩ	25,867 MΩ	0,010601	1,5929

Figure 8. Off-line measurements of C and DF

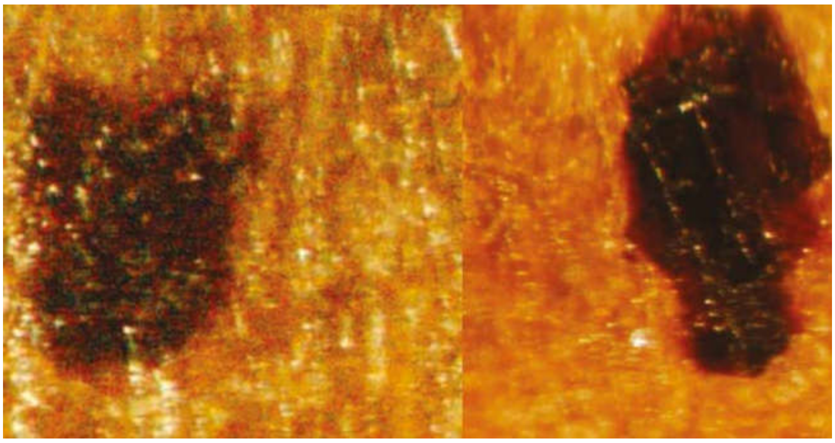


Figure 9. Evidences of PD activity in RBP bushing

> **The on-line monitoring of transformer bushings supports both field engineers in setting a more reliable diagnosis as well as asset managers in establishing proper condition-based maintenance strategies**

It is commonly accepted that the capacitance is one of the most important dielectric indicators of bushing insulation condition. In this case however, the presence of the gas cavities could not be identified as the capacitance value remained constant throughout the test, as no short circuit of a grading layer occurred. Thus by measuring the PD level and analysing the PRPD patterns, incipient condition defects can be identified before developing into serious failures.

Conclusion

For the OIP bushing, the presence of air bubbles and oil leakage were found by PD measurement. Typical PRPD patterns of these defects were identified. The bushing capacitance increased at a lowered oil level, but remained constant when the oil was contaminated with atmospheric air and transformer sludge. The design flaws of an RBP bushing tested at the U_m were also detected through PD measurement. At a test voltage of $1.15\cdot U_\mathrm{m}$, the presence of the defects were identified through off-line DF measurements as well. The bushing capacitance value remained constant, as no short circuit of the grading layers occurred during the tests. As the consideration of single parameters and the relation between their values and pre-set thresholds may be misleading, the key element of bushing defect identification is the correlation of more relevant condition indicators. As it was proved in this article, the results of partial discharge measurements do make a difference, enabling a more reliable bushing diagnosis. For the same considerations, the on-line monitoring of transformer bushings makes a lot of sense. This information supports both field engineers in achieving optimal results for a more reliable diagnosis as well as asset managers in establishing proper condition-based maintenance strategies.

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