AGEING-CONDITION ASSESSMENT OF 400 KV OIP GENERATOR TRANSFORMER BUSHINGS

M. ZINK [1, 3], F. BERGER [2], V. KLIPFEL [3], A. KÜCHLER [1]
[1] FHWS University of Applied Sciences Würzburg-Schweinfurt, Germany,
[2] Technische Universität Ilmenau, Germany
[3] EnBW Kernkraft GmbH, Kernkraftwerk Philippsburg, Germany
Email: m.zink@kk.enbw.com

Abstract: Today, most of the bushings installed in the electrical grid are insulated with OIP (oil impregnated paper) and have been designed for a life of 30 years. As many of them will reach this designed life expectancy soon or have exceeded it already, the ageing-condition assessment of those units becomes important and an estimation of their future behaviour is very desirable.
This paper reports on current investigations on three service-aged 400 kV generator transformer bushings which were in use for 30 years in a German nuclear power plant. Generally, different kinds of dielectric measuring methods are possible. Based on former experiences ([1], [2]), it could be shown that PDC measurements are a valuable tool for insulation condition assessment of the bushing insulations for the given test objects. Other methods will be applied later on. Nevertheless, measurements cannot give an absolute insight into the dielectric properties. Therefore, it is intended to use simulations with P-Spice as a tool, both to investigate the suitability of different measuring methods and to evaluate the insulation condition of the test objects in detail.
For the given test objects, the first measurement results gained with PDC measurements and the comparison with the experiences gained in former projects ([1], [2]) show that the aging was not as strong as it might be expected after 30 years of operation under high thermal and electrical stresses.

1 INTRODUCTION

Bushings are the bottlenecks in the electrical grid. They are transporting large amounts of energy and have to withstand high electrical and thermal stresses. Due to ageing effects, the impact of stresses on the insulating materials increases with time and accelerates the ageing in a self-amplifying manner. Failures in comparatively cheap bushings can cause severe failures in other strategically important components like transformers. It is assumed that 30% of transformer failures are caused by bushing failures.

Today, most of the bushings installed in the electrical grid are insulated with OIP (oil impregnated paper) and have been designed for a life of 30 years. As many of them will reach this designed life expectancy soon or have exceeded it already, the ageing-condition assessment of those units becomes important and an estimation of their future behaviour is very desirable.

There are three questions, being especially interesting for transformer operators:

1. In which condition is the insulation of 30 years old OIP bushings?
2. Which measuring methods allow a reliable evaluation of bushings?
3. Which conclusions can be drawn from the measurements and analyses?

2 TEST OBJECTS UNDER INVESTIGATION

This paper reports on current investigations on service aged 400 kV generator transformer bushings. Based on former experiences ([1], [2]), it is intended to answer the questions mentioned above.

Figure 1: Test objects – 30 year old service aged 400 kV bushings

The test objects are three service aged 400 kV OIP bushings coming from a German nuclear power plant, see figure 1 – in the following referred to as test objects. As nuclear power covers the base load on electricity supply in Germany, the bushings were operated on nominal power nearly all the time for 30 years. Now they where replaced by new RIP bushings with cores of resin impregnated paper. Therefore the test objects can now comprehendsively be investigated with different dielectric measuring methods and procedures. It is advantageous that this investigation can be performed on highly stressed 30 years old bushings with a well known load history. Thereby, both the ageing condition of the 30 years old units can be determined and the advantages and disadvantages of different methods and procedures can be compared. Primarily, dielectric measuring technologies will be applied and evaluated, such as

- conventional dielectric measurements (C, tan-δ measurements),
- step-response measurements in time-domain (PDC, polarization and depolarization current measurements),
- frequency-domain spectroscopy (FDS),
- combined PDC and FDS measurements.

At the moment, only PDC measurements were performed, so the paper can only report about those measurements. Other measurements are prepared and will be done during the further investigations of the bushings.

3 PDC-MEASUREMENTS

For diagnostic measurements each bushing has a special measurement tap that is connected to the outermost grading foil, which is normally connected to ground. At this measurement tap, the measurement device (e.g. PDC-Analyzer [3]) can be connected.

The PDC-measurement is a step-response measurement working in time-domain. The bushing is energized with a voltage step of up to 2 kV and the current through the insulation is measured, see figure 2.

As long as the voltage is applied, the current is the so-called polarization current $i_P(t)$. It contains both, time-varying polarization currents $i_{pol}(t)$ as well as nearly constant conductive currents $I_{conductive}$ resulting from the finite ohmic conductivity of the dielectric. When the voltage is switched off, the depolarization current $i_D(t)$ is driven by depolarization effects inside the dielectric material while the bushing is short-circuited.

This can also be described by an equivalent circuit diagram according to figure 3.

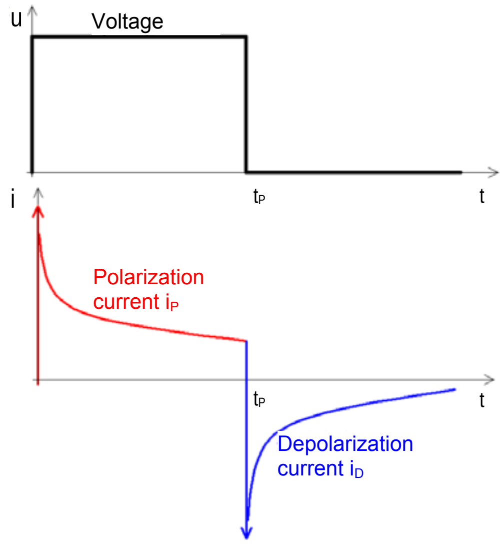

Figure 2: Step voltage and step-response current during a PDC-measurement.

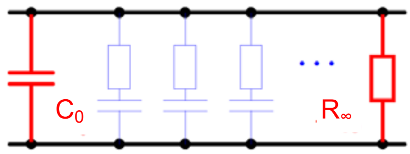

Figure 3: Equivalent circuit diagram derived from PDC-measurements.

The capacitance C_0 represents the geometric capacitance of the bushing. It is mainly the capacitance C_0 which is charged during the voltage step at the beginning of the measurement, it dominates the polarization current at first. R_∞ describes the resistance of the dielectric for long-term conditions. It determines the current $I_{conductive}$ after a long time of voltage application. The RC-components in the middle of the diagram represent the polarization effects of the dielectric with different time constants. These RC-elements cause the actual polarization current $i_{pol}(t)$.

The resulting current $i_P(t)$, which is also called polarization current, can be written as follows:

$$i_P(t) \quad = \quad i_{pol}(t) + I_{conductive}$$

The depolarization current $i_D(t)$ is determined by polarization effects and by the time of voltage application (polarization time t_P). If t_P is long enough, $i_D(t)$ is a good approximation of the actual polarization current $i_{pol}(t)$, the time-shift t_P has to be considered:

$$i_D(t) \quad \approx \quad - i_{pol}(t + t_P)$$

So the conductive part can be estimated by taking the difference of the polarization and the depolarization current magnitudes after a sufficient measuring time t.

Figure 4 shows the polarization and depolarization current gained at one of the three test objects described in chapter 2.

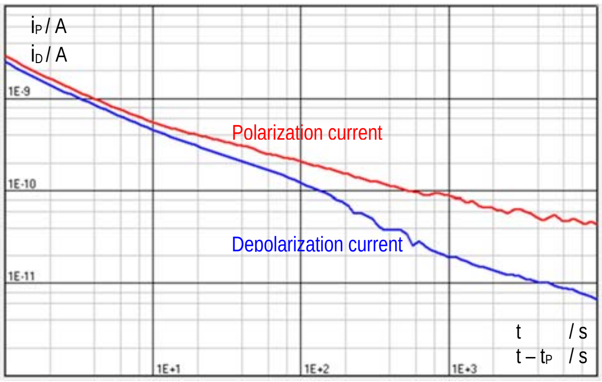

Figure 4: Polarization and depolarization currents of one of the test objects at room temperature (RT) and at 2 kV.

4 AMBIENT INFLUENCES

Former investigations have shown that special attention has to be paid to ambient influences (e.g. parasitic leakage currents due to surface contamination and transformer oil conductivity) [2].

Figure 5 shows how resistive paths can influence dielectric measurements of bushings. The upper picture explains how parasitic resistive paths coming out from the bushing's grading foils to ground are subtracted from the current through the dielectric and reduce the measured current. The lower picture shows that parasitic resistive paths from the high voltage potential to the grading foils are added to the current through the dielectric and increase the measured current. By the use of bandages that are applied at the housing insulator of the bushing, the effects described in figure 5 can be amplified. Figure 6 shows such a voltage tap built by a metal rope.

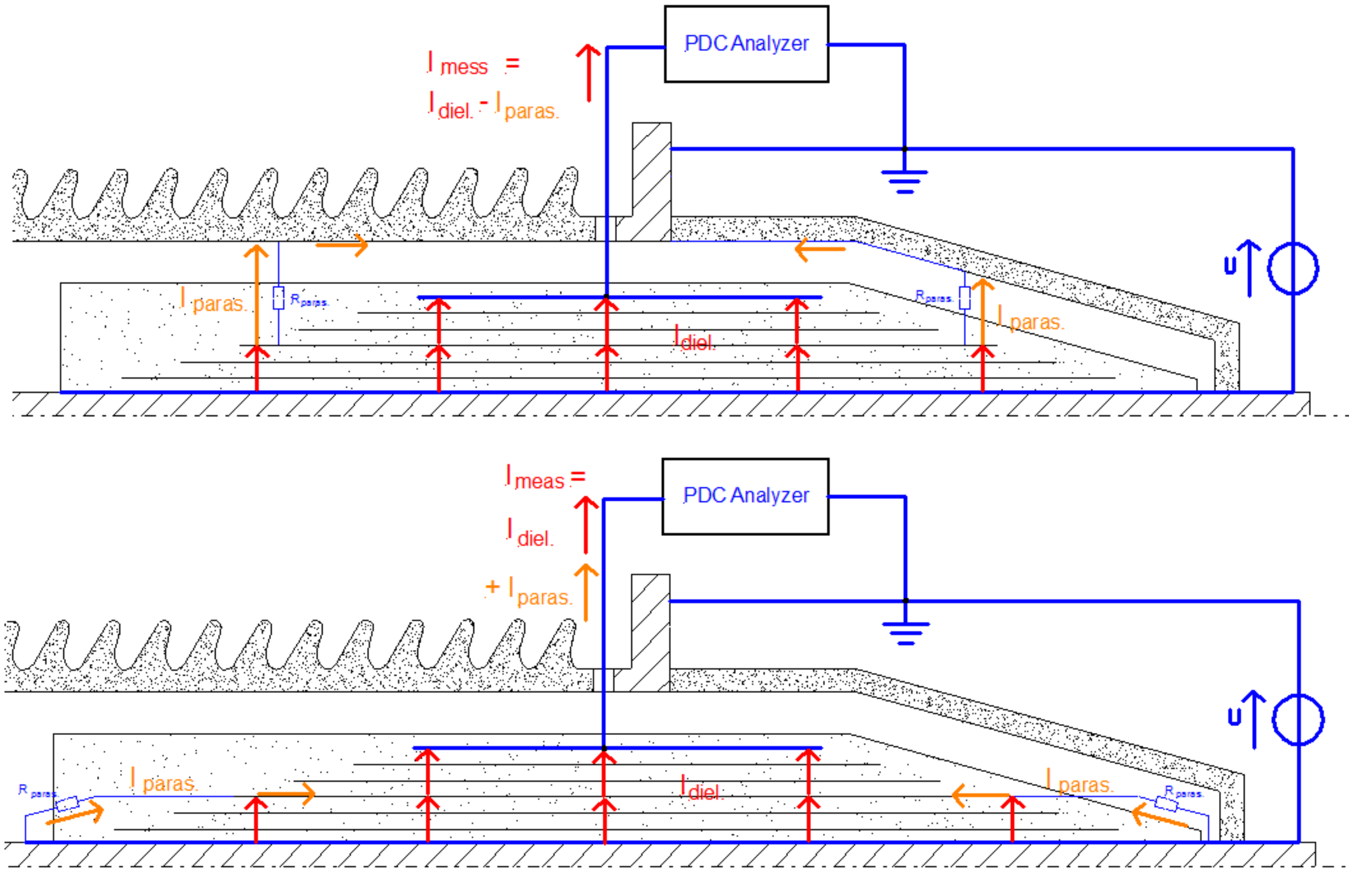

Figure 5: Influences of parasitic currents from the HV side (bottom) or to the ground (bottom) on dielectric measurements of bushings [2].

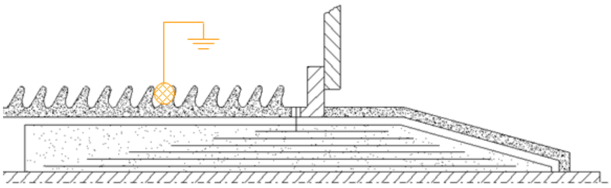

Figure 6: Grounded bandage applied at the housing insulator of the bushing.

If the bandage is connected to ground potential, the measured current is reduced, see the upper picture of figure 5. Is the voltage tap connected to high voltage potential, the current is increased, see the lower picture of figure 5.

This method can only have a significant influence on the measurement if the conductivity of the dielectric of the bushing is not too high. Otherwise, the small influence of the bandage cannot be seen in the measurement. Hence the spacing between the measurements with grounded and energized bandage can give a first impression of the condition of the dielectric.

5 RESULTS

Measurements were made with and without bandages according to the method described in chapter 3 and 4. Figure 7 shows the result of one of the three test objects according to chapter 2.

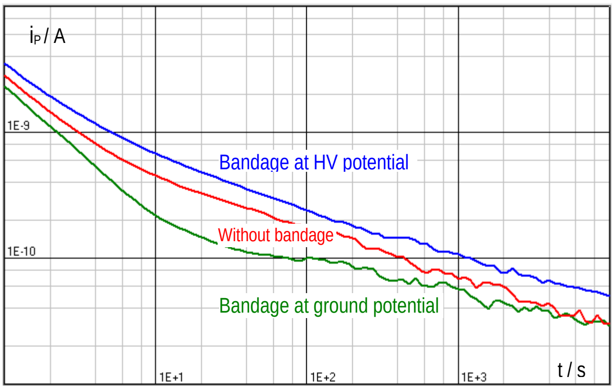

Figure 7: Polarization currents of one of the test objects without bandage, with bandage at ground potential and with bandage at high voltage potential (diagnostic voltage 2 kV, room temperature).

It can be seen that the use of energized and grounded bandages has the expected influence on the measurements as it was described before.

Figure 8 shows a comparison of the test objects. The PDC measurements were done at 2 kV and room temperature, only polarization currents are shown. It can be seen, that there is no big difference between the curves, neither for the long-term current values nor for the polarization behaviour in the beginning of the measurements. Further investigation will be done on the voltage dependence of the currents, see chapter 7.

Former investigations have shown that severely aged bushings can be detected from significantly increased polarization currents during the first seconds of voltage application, see curves (1) and (5) in figure 9 [1], [2]. Interestingly, this condition of the bushings could not be detected from power-frequency dissipation-factor measurements at room temperature, as they are usually applied during standard measurements. On the other hand, PDC measurements at room temperature and dissipation factor measurements at service temperature 70 °C clearly detected the dangerously aged OIP condition, which is close to thermal instability. The long-term values of the currents are strongly influenced by the conductivity of the OIP dielectric, which can be increased both by conductive ageing products and by absorption of water. Therefore, ageing and wetting cannot be distinguished from long-term current values alone, additional information is required. This information is provided by the polarization currents during the first seconds as described above.

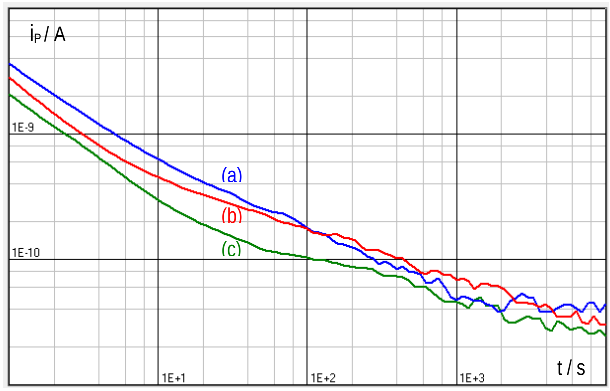

Figure 8: Comparison of polarization currents of the test objects (diagnostic voltage 2 kV, room temperature).

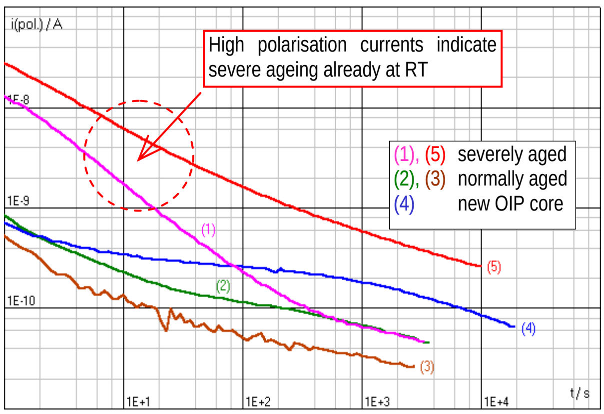

Figure 9: PDC measurements on identically designed 420 kV OIP bushings, differently aged in service, measurements at RT and 1 kV, [1], [2].

Figure 10 shows a comparison of the test objects (a), (b) and (c) according to figure 8 with the severely aged bushing (5) according to figure 9 and with a 500 kV OIP bushing (6) from a test transformer which is also about 30 years old, but which was never used under higher temperatures and thermal loads. The PDC measurement on the 500 kV bushing (6) and the measurement on the severely aged 400 kV bushing (5) were done at 1 kV, while the measurements on the test objects (a), (b) and (c) were performed at 2 kV. Therefore, the currents (a), (b) and (c) should be reduced by a factor of 2 for comparison purposes.

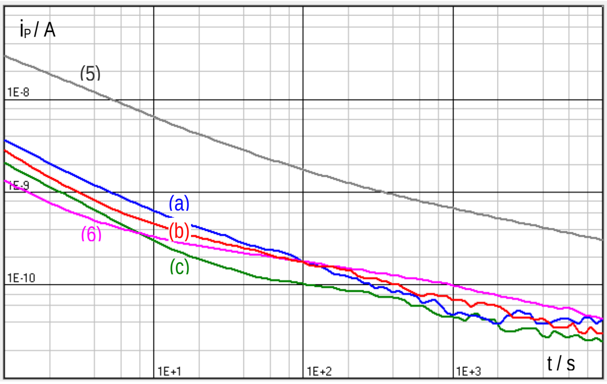

Figure 10: Comparison of polarization currents for the test objects (a), (b), (c) with a 500 kV OIP test-transformer bushing (6) and with a severely aged 400 kV OIP bushing (5). All measurements were performed at room temperature, no. (5) and (6) at 1 kV, no. (a), (b), (c) at 2 kV.

These results show that the condition of the dielectrics of the test objects (a), (b) and (c) are not so bad as it could be supposed after a 30 years of operation. The PDC measurement is a valuable tool for the condition assessment of aged OIP insulation systems. Nevertheless, the insight into the dielectric properties can still be improved. This should be gained by means of the simulations described in the next chapter.

6 SIMULATION WITH P-SPICE

Over several years, many measurements of conductivities and dielectric properties of different material samples were taken at the High Voltage Laboratory of the University of Applied Sciences Würzburg-Schweinfurt. There are several PDC and conductivity measurement data available from samples of different insulating materials including oil impregnated paper with different water contents and with different aging conditions. By means of these material data and based on a discretization of the bushing geometry, the behaviour of the bushings can be simulated. So it is possible to perform simulations with different water contents and ageing conditions, in order to find the most realistic case and hence the most likely situation inside the dielectric of the bushings.

Figure 11 shows, how the geometry of a bushing can be discretized for simulation. Each of the elements is filled with equivalent circuit diagrams both into axial and radial directions. They consider the different materials (e.g. porcellain, oil or oil impregnated paper) at different material conditions. Figure 3 shows such a diagram.

Simulations are done in the same way as real measurements: A voltage step is applied and the current through the dielectric is monitored.

At the moment, modelling and simulation of the bushings is not yet completed.

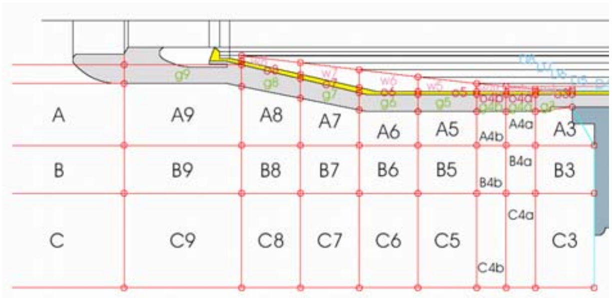

Figure 11: Geometrical discretization of the bushing for simulation (only the lower part is shown) [2].

7 CONCLUSIONS AND FURTHER ACITVITIES

PDC measurements can be applied to bushing insulations for condition assessment purposes if parasitic surface currents are considered by means of bandages. With this method, PDC measurements can detect aged OIP insulation conditions already at room temperature, which is not possible with power-frequency dissipation-factor measurements. Therefore, PDC measurements can signifycantly contribute to economic efficiency, technical reliability and safety of power apparatus.

Simulations can be used as a tool, both to investigate the suitability of different measuring methods and to evaluate the insulation condition of the test objects in detail. The next activities will be to complete the simulation model presented in chapter 6. Simulation results will be compared with the measurements applied at the bushings – see chapter 3.

Regarding the measuring methods, the following questions will be investigated: Nonlinearities of dielectric measurements will be investigated by

PDC measurements at higher voltages up to 100 kV. Measurements in frequency domain (FDS) will be completed and compared, as one of the main tasks of the project is to find out, which measurement method seems to be the best for the assessment of the bushing condition.

8 ACKNOWLEDGMENTS

Authors gratefully acknowledge the financial support of the project by EnBW Kernkraft GmbH. Additionally, they want to thank Jan Ritter, Steffen Voll, Franz Klauer and Mario Sinder for their support.

9 REFERENCES

[1] A. Küchler, F. Hüllmandel, K. Böhm, N. Koch, K. Loppach, Ch. Krause, J.J. Alff; Condition Assessment of Aged Transformer Bushing Insulations; CIGRÉ 2006 Session, paper A2-104, Paris, 2006

[2] F. Hüllmandel, M. Appold, A. Küchler, R. Krump, J. Titze; Condition Assessment of High Voltage Bushings by Means of Dielectric Diagnosis with PDC; ISH 2007, paper 172-00, Ljubljana 2007

[3] 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