UHF Partial Discharge Measurement for Acceptance Tests of Power Transformers

Stefan Tenbohlen, Martin Siegel

***Abstract*— The reliability of electrical energy networks depends on the quality and reliability of its electrical equipment, e.g. power transformers. Local failures inside their insulation may lead to catastrophic breakdowns and may cause high outage and penalty costs. To prevent these destroying events, power transformers can be tested on partial discharge (PD) activity before commissioning and monitored during service. In this contribution, a calibration procedure for the ultra-high frequency (UHF) method is proposed as it is necessary to ensure reproducibility and comparability of UHF measurements. Afterwards, a calibrated UHF method can be introduced supplementary to IEC60270 in acceptance tests of power transformers. This contribution compares the calibration procedures of the conventional electric method (IEC60270) and the electromagnetic method. A characterization of UHF sensors by the antenna factor (AF) is a precondition for the UHF calibration procedure. To provide profound knowledge of the equipment, the AF of the UHF sensor is determined under inside transformer conditions. To meet these conditions, an oil-filled GTEM cell is used for correct permittivity. Additional to the calibration procedure, the performance of the installed sensor has to be determined. The evaluation is based on the idea of transmitting electromagnetic waves through the transformer tank from one UHF sensor to another which is called performance check procedure.**

Keywords: Power Transformers, Partial Discharge, Monitoring, Calibration.

I. Introduction

Power transformers can be considered as an essential part to assure the reliability of the electrical grid. Transformer failures lead to consequential damage with accordant costs. Reliable operation of power transformers is fundamental for service security. Therefore, damages to the insulation of a power transformer, like local defects, must be recognized at an early stage [1]. Different diagnostic methods have been established to meet the deriving demands for onsite and factory measurements. There are mainly three different ways of PD monitoring: indirectly by dissolved gas analysis (DGA) monitoring, directly by PD measurement method according to IEC60270 [2] and directly by electromagnetic measurements [10] in the ultra-high frequency range (UHF: 300 MHz - 3 GHz). Measurements of acoustic emissions are mainly used to supplement diagnostic measurements for PD localization [7] purposes and are not regarded in this contribution. Because DGA only provides an indicator of the presence of PD, an increasing number of transformers are monitored directly. The importance of PD measurement is accommodated by standardized electrical measurement (IEC60270) which is required for acceptance certificates at routine testing. Therefore, the apparent charge Q_{IEC} has become an indicating factor for transformer quality. The UHF method is based on the measurement of electromagnetic waves radiated by PD. First, UHF measurements were used for gas insulated switchgears (GIS) [3]. When applied on transformers, the UHF method requires antennas inside the tank. Hence, the Cigré Working Group WG A2-27 recommends DN50 valves or dielectric windows for the fitting of UHF probes in brochure 343 [4]. The generalized propagation paths of the methods are shown in Fig. 1.

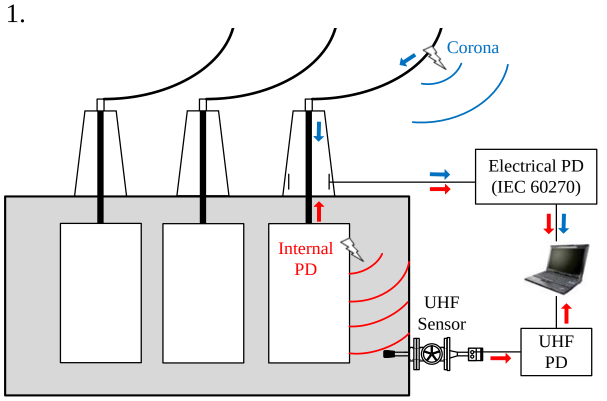

Fig. 1 Signal propagation of UHF and conventional PD measurement at a power transformer with internal (red) and external PD (blue) [6]

Electrical signals travel through the galvanic and capacitive coupling along the winding and are decoupled at the measurement capacity of the bushing (online monitoring) or with an external coupling capacitor (not shown). Electromagnetic signals radiate directly through the oil-filled transformer. Additionally, UHF PD measurements are usually electromagnetically shielded against external disturbances, e.g. corona, by the grounded transformer tank itself [5,10]. UHF measurements have been established as a trigger for acoustic PD localization [7] and for onsite/online diagnostic PD measurements [8] and seem to be suitable for online PD monitoring [9]. To become an accepted quality verification factor, UHF technology has to be proven reliable in order to supplement electrical measurements. Basically, a

Stefan Tenbohlen is with the University of Stuttgart, Pfaffenwaldring 47, 70569 Stuttgart, Germany (phone: +49/711/68567870; e-mail: stefan.tenbohlen@ieh.uni-stuttgart.de).

Martin Siegel is with the BSS GmbH, Steinstr. 29, 71229 Leonberg, Germany (phone: +49/711/21954656; e-mail: martin.siegel@bss-hs.de).

calibration procedure which makes UHF sensors and measurement systems comparable to each other is lacking so far. Due to that, the UHF technology is by now not applied as criteria for acceptance tests and mainly used for supplement diagnostic measurements or online monitoring systems. For electrical PD measurement, on the contrary, there is an available calibration procedure for the ratio between capacitance of specimen and coupling capacitor. The associated comparability of electrical PD measurement systems has led to an acceptance level at transformer routine tests, although the actual PD charge still remains unknown.

II. UHF Calibration Proposal

To achieve a comparable method, UHF measurement systems require calibration including a validation of the UHF antenna sensitivity. Therefore, the antenna factor of UHF sensors needs to be determined in a defined setup as presented in chapter III and can afterwards be included in the calibration procedure of UHF measurement systems.

A. *Calibration Procedure of Measurement Device and Cables*

A known UHF calibration impulse is injected into the measurement setup without antenna in order to calibrate the cable and the measurement device itself, see Fig. 2.

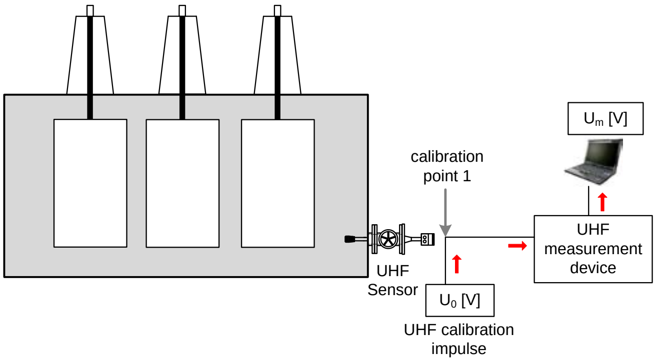

Fig. 2 Calibration of measurement device and cables

From this calibration measurement, the calibration factor K_1 can be calculated:

$$K_1 = \frac{U_0}{U_m} \quad (1)$$

B. *Calibration Procedure of the UHF Sensor*

In order to include the sensor's characteristic into the calibrated path, its AF(f) is required. The actual insertion depth has to be the same during AF determination and UHF measurement (here: 50 mm). The known transfer function provided by the AF allows the shifting of the calibration point from the injection point of the calibrator to the UHF antenna inside the transformer. In order to simplify the calibration procedure for broadband measurement systems, the frequency dependent AF(f) can be reduced to a scalar correction factor AFs which represents most common occurring UHF PD frequencies with sufficient accuracy. It is proposed to use the mean AF(f) from 300 MHz to 1 GHz as scalar. Therefore in a first step the AF(f) is calculated in its delogarithmized form $AF(f)_{lin}$.

$$AF(f)_{lin} = 10^{\frac{AF(f)}{20}} \quad (2)$$

In a second step the mean value of the AF in the corresponding frequency range is calculated, which is correction factor K_2.

$$K_2 = mean_{300\,MHz}^{1\,GHz}\, AF(f)_{lin} \quad (3)$$

Fig. 3 shows an example of simplifying the AF(f) to a simplified mean AF_s (delogarithmized used as K2) and Fig. 4 the new calibration point which is shifted inside the transformer to the UHF antenna.

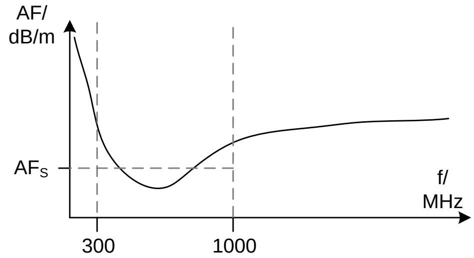

Fig. 3 Example of simplifying the AF

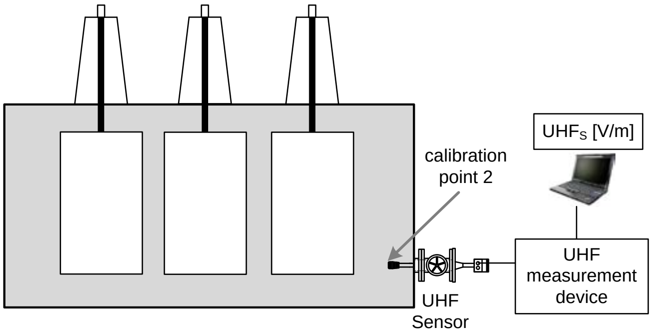

Fig. 4 Calibration point of the UHF Sensor

The idea of using a mean value of the frequency dependent AF(f) is only valid for broadband UHF measurement systems. When using a narrowband measurement system, the actual $AF(f_{center})$ at the center frequency should be used for K_2.

C. *Calibration Procedure of the entire UHF Measurement System*

The complete UHF calibration factor K_{UHF} is calculated:

$$K_{UHF} = K_1 \cdot K_2 \quad (4)$$

An impulse U_i measured with the UHF measurement system can now be corrected and results in a value correlated to the incident electrical field at the UHF sensor, which is radiated by PD. This value can be called "apparent field strength" (E_{UHF}) like "apparent charge (q)" of the electrical PD measurement. It is called "apparent" because it is not directly related to the actual PD value itself but its calibration makes different measurement systems (including UHF sensors, cables, amplifiers, attenuators, filters and measuring devices) comparable.

$$E_{UHF} = K_{UHF} U_i \quad (5)$$

D. *Performance Check*

A performance check based on a second (emitting) UHF sensor inside the transformer is always necessary because the calibration procedure does not demonstrate the performance of the antenna to electromagnetical signals from inside of the transformer. Although calibrated, UHF PD measurement might be impossible due to internally electromagnetical shielded sensors, e.g. by tubes.

E. Comparison of Electrical and UHF Calibration Procedure

Often, calibration of UHF sensors is used as a synonym for the relation between measured UHF antenna voltage (in mV) and apparent charge (in pC) of the electrical measurement. As the apparent charge level needs to be treated with caution, this link is not necessary as well as impossible. For this reason, a general consideration of calibration methods for UHF and electrical measurements are determined and compared. Fig. 5 shows in conclusion both calibration procedures and which Transfer Functions (TF) are included or excluded in the calibrations or can be included by measurement of its TF (in case of the AF of UHF sensors).

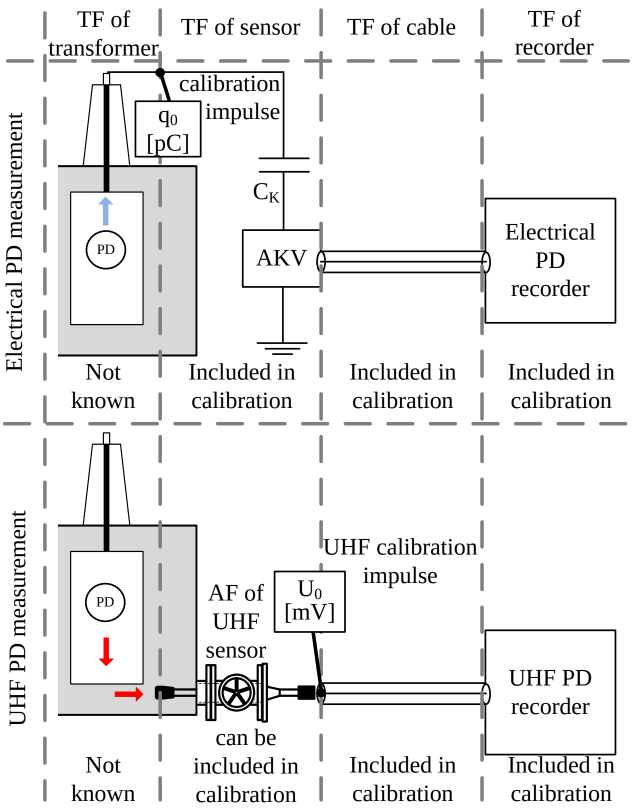

Fig. 5 Comparison of PD calibration methods.

The propagation mechanisms of electrical and electromagnetic signals inside the transformer are fundamentally different and so are the attenuations of the signals. The winding conductor serves as propagation path in the electrical PD measurement. The propagation of the electromagnetic signals in the UHF range is a radiated emission in the entire volume of the transformer, in oil and pressboard. Thereby, the electromagnetic wave is attenuated and can be reflected by metallic parts. In both cases, the TF inside the transformer remains unknown and cannot be included in a calibration procedure. The AF of UHF sensors can and must be included in a calibration procedure in order to ensure comparable results when using different measurement devices and UHF sensors.

III. Characterization of UHF Sensors

Both, the measureable electrical and the UHF PD levels, are influenced by the

- type and actual level of the PD source
- signal attenuation in the coupling path
- sensor sensitivity (the UHF antenna or the coupling capacitor and the quadrupole)
- attenuation of the measurement cable and the sensitivity of the measurement device

The influence of the electric setup (coupling capacity and quadrupole) and the measurement device can be corrected using calibration for the electric measurement (IEC60270). A comparable calibration to compensate the UHF sensor's influence can be achieved. In order to determine the sensor sensitivity, the UHF antenna factor (AF) must be known. In previous investigations, the AF of UHF sensors was determined within an air-filled TEM cell in a frequency range up to 950 MHz [10]. Because of the different permittivities ($\varepsilon_{r,air} = 1$, $\varepsilon_{r,oil} \approx 2{,}3$), the AF measured in air does not apply to transformer oil and needs to be shifted in frequency range to meet the different wave propagation speeds of oil and air. Furthermore, the full bandwidth of UHF sensors cannot be tested with conventional TEM cells. Hence, proper AF determination requires an oil-filled measurement setup capable of full UHF frequency range. To meet these conditions, an oil-filled Gigahertz-Transversal-Electro-Magnetic Setup (GTEM cell) is required [11].

A. Antenna Factor (AF)

The antenna sensitivity depends on its design in relation to the electromagnetic wavelength. Antennas are described by different characteristics, e.g. by the effective length l_{eff} or the antenna factor AF which is the following:

$$AF(f) = \frac{E(f)}{U(f)} \qquad (6)$$

where U(f) is the voltage at the antenna terminals and E(f) the electric field strength at the antenna. An appropriate special designed oil-filled GTEM cell [6,11] is used for the evaluation of the antenna sensitivity (Fig. 6).

Fig. 6 GTEM cell external view

A GTEM cell is an expanded coaxial conductor where a defined electromagnetic field can be applied to equipment under test (EUT) without interference from the ambient electromagnetic environment. In the cell, a test volume is defined in which the EUT is situated. In the test volume, the cell ideally provides a homogeneous electric field distribution E_{hom} and an orthogonal magnetic field of the TEM wave. In addition, the electric field strength E_{hom} in the test volume has to be known for AF calculation of the EUT.

B. Antenna Factor Measurement with oil-filled GTEM Cell

The AF of a UHF sensor can be determined using a transmission factor (S21) measurement, see Fig. 7. The entire setup consists of the oil-filled GTEM cell with inserted UHF sensor and the vector network analyzer (VNA). The sensor insertion depth should be the same as in later PD measurements; here: 50 mm.

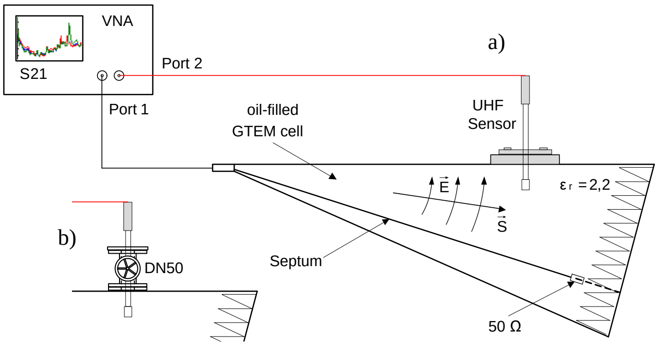

Fig. 7 Transmission measurement (S21) for AF determination
a) UHF sensor directly mounted to the cell without oil valve
b) UHF sensor installed via DN50 oil valve to the cell

In this setup, the input port of the GTEM cell is excited with a sinusoidal frequency sweep from 300 kHz to 3 GHz generated by the VNA. The second port of the VNA simultaneously measures the resulting voltage at the output of the UHF sensor. The resulting transmission factor S21 can be converted into the AF of the UHF sensor if the electric field strength in the test volume is taken into account. Two different AF of a UHF drain valve sensor are presented in Fig. 8.

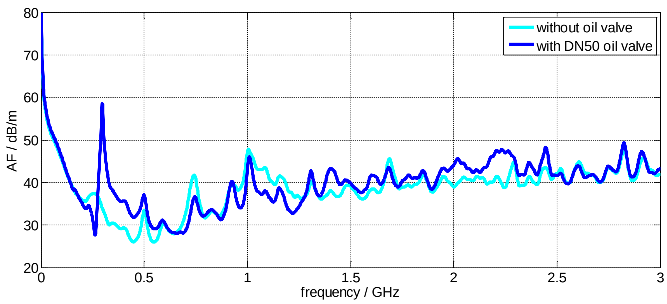

Fig. 8 Antenna factor (AF) of UHF sensor measured in GTEM cell
Light Blue curve: UHF sensor directly mounted to the cell (Fig. 7 a))
Dark Blue curve: Mounted via DN50 drain valve to the cell (Fig. 7 b))

The UHF sensor has the highest sensitivity in the frequency range of 300 MHz up to 1 GHz. The measurement of the light blue curve is done without a standard oil valve at the GTEM cell. The influence of oil valves on the sensor's AF is not negligible like the curves in Fig. 8 show. The highest influence of the valve occurs at approx. 300 MHz.

IV. Conclusion

The UHF method requires a calibration process, similar to the calibration of the electrical measurement (IEC60270). Otherwise, measurements of different systems cannot be compared which is a basic requirement for an accepted PD test method. In contrast to the electrical measurement, it is not possible to calibrate the entire UHF measurement path because the UHF sensor is excluded from the calibration path between calibrator and PD recording unit. Therefore, the sensor's characteristics have to be obtained separately and then included into the system calibration. A standard setup like the presented oil-filled GTEM cell provides sensor characteristics by measuring the antenna factor (AF). The proposed calibration is done by injecting a known impulse into the UHF measurement system without UHF sensor and using the AF to include the characteristic of the antenna. As the calibration does not demonstrate the sensitivity of the installed UHF sensor to electromagnetical signals, a performance check has to be done additionally using a second (emitting) UHF sensor. The proposed UHF calibration procedure is essential for comparable UHF measurements independent of the used sensors, cables and measuring devices. Thus, a standardization of the UHF method can be achieved and acceptance levels for factory and site acceptance tests (FAT and SAT) can be defined in the future.

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