Application of UHF Sensors for PD Measurement at Power Transformers

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ABSTRACT

The reliability of electrical energy networks depends on both, the quality and reliability of its electrical equipment, e.g. power transformers. Local failures inside their insulation may lead to breakdowns and hence to high outage and penalty costs. Power transformers can be tested on partial discharge (PD) activity before commissioning and monitored during service in order to prevent these events. In the first part, this contribution presents different types of ultra-high frequency (UHF) sensors for PD measurement. Various applications of UHF sensors and proper sensor installation are discussed. The second part of the contribution is about the necessity of UHF measurement comparability and reproducibility. Therefore, a new calibration procedure for the UHF method is proposed and discussed in respect of the procedure for the IEC 60270 compliant conventional electric method. The characterization of UHF sensors is a key precondition for the UHF calibration process in order to obtain calibration for the full measurement path. Sensor characteristics are described by the antenna factor (AF) which is determined under inside transformer conditions in an oil-filled Gigahertz Transversal Electromagnetic cell (GTEM cell). In addition to the calibration procedure, the performance of the installed sensor has to be determined. The evaluation is based on the concept of transmitting electromagnetic waves through the transformer tank from one UHF sensor to another. This performance check procedure is used in this contribution for the examination of the influence of the sensor's insertion depth into the tank. These results are compared to the reference GTEM cell measurement used for calibration.

Index Terms — **Power transformers, partial discharges, UHF measurements, UHF antennas, calibration.**

1 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 [1]. Therefore, damages to the insulation of a power transformer, e.g. local defects, must be recognized at an early stage [2]. Different diagnostic methods have been established to meet the deriving demands for on-site and factory measurements [3]. The dissolved gases analysis (DGA) provides an indicator of the presence of PD. Besides the conventional electrical PD measurement method according to IEC 60270 [4], there are mainly two different alternative PD measurement methods: The measurement of electromagnetic signals [5] in the ultra-high frequency range (UHF: 300 MHz - 3 GHz) radiated by PD and the measurements of acoustic PD emissions. The acoustic method is mainly used to supplement diagnostic measurements for localization of PD [6]. The UHF method seems to be suitable for various applications at power transformers [5, 7, 8] and requires antennas inside the tank. Therefore, the Cigré Working Group A2-27 recommends DN50 valves or dielectric windows for the fitting of UHF probes [9]. The physical transmission paths of PD signals recorded with electrical and UHF measurement methods fundamentally differ from each other. Electrical signals travel through the galvanic and capacitive coupling along the winding and are decoupled at the measuring tap of the capacitive graded bushing, or with an external

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coupling capacitor. Electromagnetic UHF signals radiate directly through the oil-filled transformer and can be measured with specially designed antennas for transformer installation. In addition, UHF PD measurements are usually electromagnetically shielded against external disturbances, e.g. corona, by the grounded transformer tank itself [7, 5]. To become an accepted quality verification factor, UHF technology has to be proven being reliable, reproducible and hence comparable. This can be realized by a standardized calibration procedure which is not available yet. This disqualifies the UHF technology as a criterion for acceptance tests.

Different UHF sensors types and their applications at power transformers are presented in chapter 2 and 3. The characterization of these sensors and the equipment needed is discussed in chapter 4. A proposal for UHF calibration is introduced in chapter 5 in order to meet the above-mentioned requirements. An investigation on the insertion depth of the variable UHF sensors results in a recommendation for sensor installation in chapter 6.

2 UHF SENSORS

An UHF Sensor for power transformers consists of a broadband antenna suited for the UHF frequency range radiated by PDs and of its mechanical adaption for the installation at power transformers. Mainly two UHF sensor technologies for internal PD measurement and one UHF sensor type for external reference measurement are used for practical applications. Additionally, a combined PD sensor for UHF and acoustic PD measurement, which is in development, is presented.

2.1 UHF DN50/DN80 DRAIN VALVE SENSORS

An UHF drain valve sensor is designed as retrofit solution for transformers which have standardized DN50 or DN80 gate valves. Figure 1a shows the standardized gate valve with a straight duct where an UHF drain valve sensor can be installed. Also ball and guillotine valves can be used for sensor installation. Figure 1b illustrates a globe valve without straight opening which is not suited for drain valve sensor application.

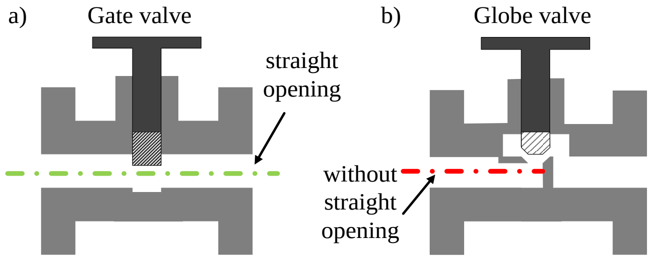

Figure 1. Possible vs. impossible oil valves for UHF sensor installation.

Other valve types without straight opening (diaphragm and butterfly valves) are also popular. As they are not applicable for UHF sensor installation, it is recommended to use only straight opening valves at new transformers.

The UHF sensor is mounted on the valve. The valve is opened slowly and de-aerated by a small screw on the sensor's mounting plate. As soon as the air is pushed out of the oil valve, it can be opened completely and the sensor can be inserted into the transformer tank. The position of the antenna in relation to the tank wall determines its sensitivity; see Figure 14 and Figure 16. Besides sensitivity considerations a minimum distance between UHF sensor and parts on high potential must be preserved to ensure save operation. This UHF sensor type can be installed at power transformers in service. Therefore, it is mainly used during diagnostic measurements on-site.

2.2 UHF PLATE SENSORS

UHF plate sensors can be mounted directly to the tank wall of newly built transformers. A dielectric window is integrated into the tank wall and consists of a stainless-steel welding ring and the dielectric window itself. It acts as an oil barrier and is made of a high-performance plastic which resists insulating oil and high temperatures. The plastic has a permittivity similar to insulating oil which allows UHF signals to pass to the UHF sensor with low damping. The plate sensor is mounted into the dielectric window and hence also reaches into the transformer tank. In contrast to the drain valve sensor, plate sensors allow UHF measurements and sensor swapping without oil handling. Figure 2 shows a dielectric window with welding ring for installation at transformer tank walls.

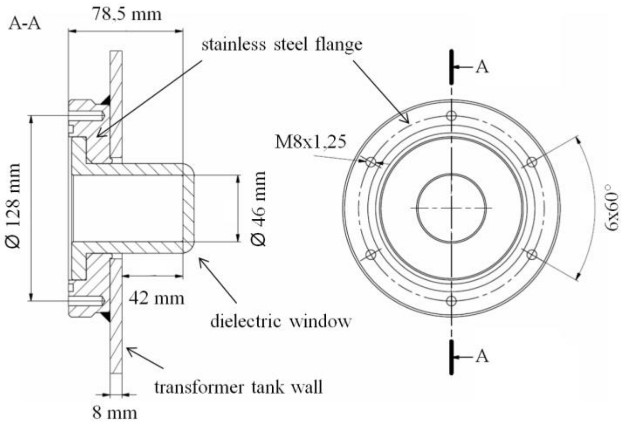

Figure 2. Dielectric window and welding ring for UHF plate sensors.

The welding ring and the dielectric window can be included into the transformer tank at any suited position whereas appropriate positioning of UHF plate sensors can significantly increase measurement sensitivity. Even if no sensors are installed at the delivery of a transformer, oil-sealed dielectric windows with a blank cover can be mounted during production to the tank wall to allow an easy retrofit of UHF PD monitoring during service.

2.3 EXTERNAL REFERENCE UHF SENSORS

The shielding of the Faraday cage is reduced at transformers with high diameter low voltage bushings (e.g. generator step-up units). Therefore, UHF signals from external PD can couple through these bushings and superimpose with inside transformer PD signals. External reference UHF sensors can be used for signals masking: signals common measured with external and internal sensors simultaneously can be excluded from further analysis.

2.4 COMBINED UHF AND ACOUSTIC IN-OIL PD SENSOR

A sensor that is able to measure UHF and acoustic PD signals at the same time is in development. Figure 3 shows a prototype of the sensor and the needed frequency filter for separation of UHF and acoustic PD signals. The sensor is designed for DN50 and DN80 oil valves. Conventional acoustic PD measurement uses acceleration sensors on the transformer tank wall. In contrast to these sensors, no external disturbances are superimposed to the acoustic PD signals at the combined in-oil PD sensor and structure borne damping is avoided.

Figure 3. Combined in-oil PD Sensor for UHF and acoustic PD detection with frequency filter and amplifier

The UHF signal sensitivity of the combined sensor is slightly lower than the UHF-only sensors' but test measurements indicate sufficient sensitivity for diagnostic measurements and online monitoring purposes. Figure 4 shows the transfer functions of the frequency filter used to separate UHF and acoustic signals. The acoustic part is designed as amplifying bandpass from 50 to 300 kHz with a gain of approx. 20 dB, the UHF part as a passive high pass. Future prototypes/sensors will include amplification for the UHF path and an increased gain of the acoustic channel. In addition, the cut-off frequencies of the filters can be tuned.

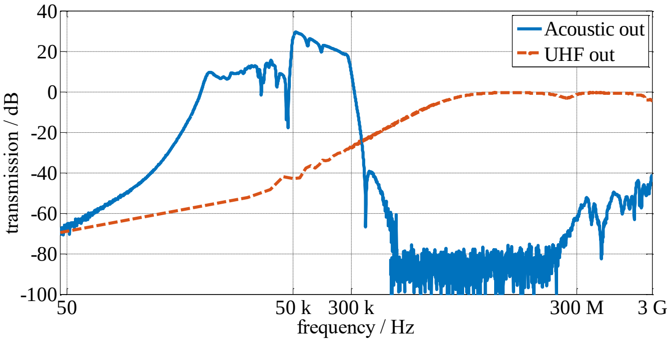

Figure 4. Transmission characteristic of frequency filter with integrated amplifier.

3 RANGE OF APPLICATION FOR UHF SENSORS AT TRANSFORMERS

In recent years, a growing demand for on-site/online PD diagnostics with high measurement sensitivity has led to the development of PD decoupling and measurement methods to overcome certain drawbacks of the conventional electrical method. Combining UHF and/or other sensor technologies with suitable instrumentation and data processing provides a series of advantages such as:

- Ease of distinguishing between internal and external PD signals by using the Faraday's cage shielding effect of the transformer tank for UHF detection
- Diagnostic "double checks" and possibly deeper insight into deterioration processes, e.g. through comparison with IEC 60270 measurement results
- Geometric PD localization by a combination of UHF and acoustic methods or the sole application of one of the methods
- PD decoupling methods without galvanic contact to any high voltage components like current transformers (CTs), transient earth voltage (TEV) or UHF sensors [10] [11]

3.1 TRIGGER FOR ACOUSTICAL PD LOCALIZATION

PD localization is mostly based on the time of flight differences between acoustic PD signals from sensors spread on the transformer tank. The emitted acoustic waves of PD are measured with piezo-electric sensors installed on the outside tank wall. Due to the high acoustic signal attenuation within transformers, sensitive acoustic measurements can be hard to achieve [6]. Additionally, acoustic signals of PD might be superimposed by external or internal mechanical noises, e.g. core noise. To increase the sensitivity of acoustic measurements, it is often combined with the UHF measuring method. UHF signals are used as trigger for the acoustic measurement for two reasons:

- Compared to the propagation speed of acoustic PD signals in oil (approx. 1400 m/s), UHF signals are significantly faster (approx. 200.000 km/s). Hence, the UHF signal can be used as temporal origin for PD with negligible small error and only three acoustic sensors are needed for the localization algorithm.
- By using averaged acoustic time domain signals, the acoustic PD pulses superimpose constructively, whereas the noise is averaged to zero.

The achievable accuracy lies within the range of centimeters [6] which is sufficient for power transformers' large geometries.

3.2 UHF PD LOCALIZATION

Time of flight measured in the UHF range can also be used for PD localization. Due to the high propagation speed, time differences between two UHF sensor's signals are in the range of nano seconds (ns). Therefore, high sampling rates and high analog bandwidth are needed. Using UHF sensors for localization, the actual time of flight from the PD source to the respective UHF sensor is not directly measurable. In addition to the unknown PD coordinates (x, y, z), the time delay Δt between the temporal origin of PD and the first measured UHF impulse has also to be solved by a localization algorithm. Hence, at least four UHF sensors are needed to provide a three-dimensional position. If there are only two or three UHF sensors installed at a transformer, either the phase or the tap changer with the located PD can be roughly determined. In that case, a three-dimensional position cannot be provided [5].

3.3 ROUGH PD LOCALIZATION USING THE COMBINED PD SENSOR

The idea of using a standard oil filling valve to insert two different types of sensors (UHF sensor and acoustic sensor) for rough PD localization was found in [12]. It can be improved by using the combined sensor as described in chapter 2.4. The localization method is the same: an UHF signal defines the temporal origin and the time of flight difference to the acoustic signal allows the estimation of the distance to the PD source. This results in a spherical surface as explained in [5]. The intersection between spherical surface and active part indicates potential PD sources. With known active part design it is possible to identify critical structures known for PD issues (e.g. the lead exit).

3.4 FACTORY AND SITE ACCEPTANCE TESTS

The increasing use of UHF technology for condition assessment of transformer insulation has led CIGRE to launch a working group dealing with the improvement of PD measurement for factory and site acceptance tests (FAT and SAT) by using supplementary UHF measurements. These results are expected to be published within the next years.

3.5 PD MONITORING

Conventional electrical PD online monitoring is often affected by external noise like corona discharges on overhead lines or bus bars. PD monitoring using UHF sensors measures only electromagnetic emission of internal PD pulses ideally. The UHF technology uses the transformer tank as a Faraday cage and can therefore be selective for PD inside the transformer [13].

3.6 UHF GATING

Electrical PD detection might be improved by the combination of the UHF technology [8]. The aforementioned drawback of high disturbances coming from corona can be reduced by the help of UHF sensors which only measure signals from the inside of a transformer. The signals from UHF sensors can be used for gating of the electrical PD measurement, e.g. by activating the electrical measurement when UHF signals from the inside of a transformer occur. This is also possible the other way round, by deactivating the electrical measurements when external UHF signals are measurable using an external reference UHF sensor (chapter 2.3).

4 CHARACTERIZATION OF UHF SENSORS

To become a comparable PD measurement method, the sensitivity of UHF sensors has to be determined. For this purpose the antenna factor (AF) is used. In the following both the test setup for AF measurement and AFs of different UHF sensor configurations will be introduced.

4.1 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:

$$AF(f)=\frac{E(f)}{U(f)} \tag{1}$$

Where $U(f)$ is the voltage at the antenna terminals and $E(f)$ the electric field strength at the antenna. Hence, a small AF means higher antenna sensitivity and is preferable. In previous investigations, the AF of UHF sensors was determined within an air-filled TEM cell in a frequency range up to 950 MHz [5]. Because of the different relative permittivities ($\varepsilon_{\mathrm{r,air}} = 1$, $\varepsilon_{\mathrm{r,oil}} \approx 2.3$), 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 [14]. Furthermore, the full bandwidth of UHF sensors cannot be tested with conventional TEM cells. Hence, a proper AF determination requires an oil-filled measurement setup capable of full UHF frequency range. To meet these conditions, an oil-filled GTEM cell is required [15, 16]. 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.

4.2 ANTENNA FACTOR MEASUREMENT WITH AN OIL-FILLED GTEM CELL

The AF of a UHF sensor can be determined using a transmission factor (S21) measurement, see Figure 5. The entire setup consists of the oil-filled GTEM cell with inserted UHF sensor and a vector network analyzer (VNA). The sensor insertion depth is variable. The insertion depth used in the cell should be the same as for actual transformer installations; 50 mm is used here.

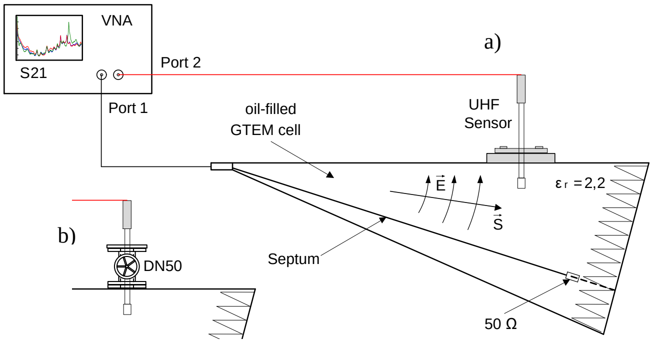

Figure 5. Transmission measurement (S21) for AF determination.
a) UHF sensor directly mounted to the cell without oil valve.
b) UHF sensor installed via DN50 oil valve to the cell.

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. Two different AF of an UHF drain valve sensor are presented in Figure 6. The UHF sensor has the highest sensitivity in the frequency range of 300 MHz up to 1 GHz. The measurement of the 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 red curve in Figure 6 indicates.

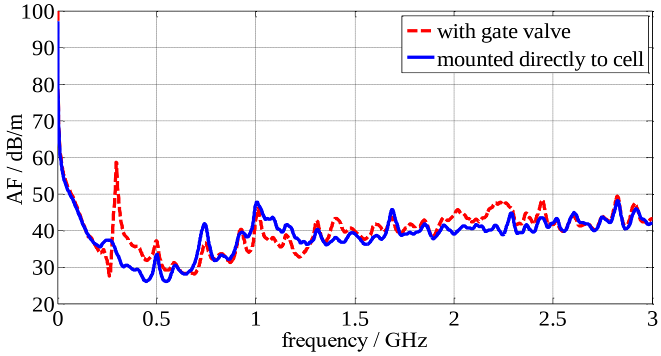

Figure 6. Antenna factor (AF) of UHF sensor measured in GTEM cell
Blue curve: UHF sensor directly mounted to the cell (Figure 5a)
Red curve: Mounted via DN50 drain valve to the cell (Figure 5b).

The highest influence of the valve occurs at approx. 300 MHz. The aforementioned three different UHF sensors for internal UHF measurement are tested and compared in the GTEM cell. Figure 7 represents the three sensor types installed directly at the GTEM cell without gate valve. The external sensor is not tested inside the oil-filled cell as its application is not inside transformer oil.

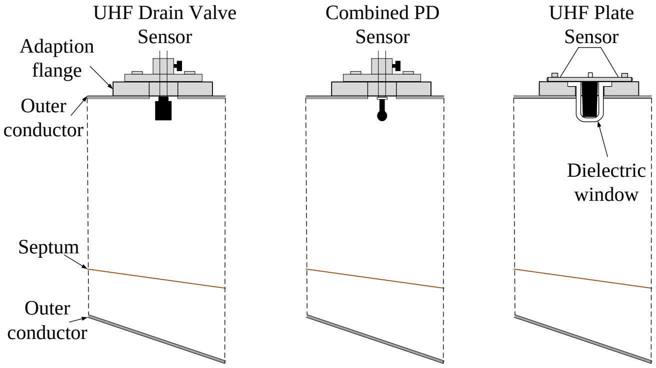

Figure 7. UHF sensors in GTEM cell, all at the same insertion depth

All sensors are tested at the same insertion depth given by the plate sensor's fixed insertion depth. In Figure 8, the AFs are presented for comparison of the UHF sensors.

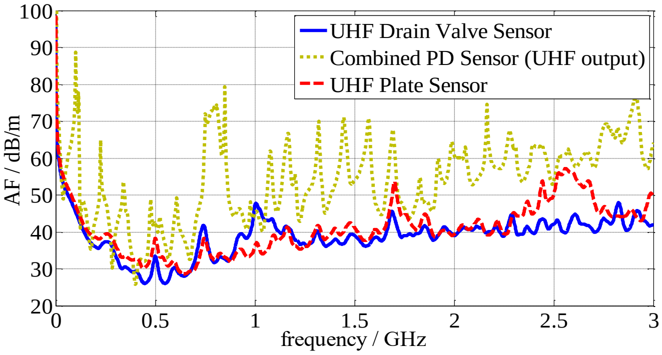

Figure 8. AFs measured in GTEM cell of the sensor arrangements in Figure 7

All three sensors are not influenced by an oil valve in this measurement setup. Therefore, the local maximum at 300 MHz does not exist at the AFs of UHF drain valve and combined PD Sensor. UHF drain valve and plate sensor are comparable in the frequency range $f = 500$ MHz…1.6 GHz. At higher frequencies, the UHF drain valve sensor is slightly more sensitive due to two local maxima of the UHF plate sensor at 1.7 and 2.6 GHz. In a general comparison, both sensor types are suited for transformer application. The plate sensor is considered slightly advantageous because it cannot be influenced by a gate valve in the usually used frequency range $f < 1$ GHz. The combined PD Sensor is not as sensitive as the two other UHF sensors, illustrated by the high peaks at various frequencies caused by resonances.

5 CALIBRATION OF THE UHF METHOD USING THE ANTENNA FACTOR

The antenna factor of UHF sensors presented in the previous chapter can be included in the calibration procedure of UHF measurement systems which is proposed in this chapter.

5.1 CALIBRATION PROCEDURE OF MEASUREMENT DEVICE AND CABLES

A known UHF calibration impulse is injected into the measurement setup without UHF sensor in order to calibrate the cable and the measurement device itself, see Figure 9.

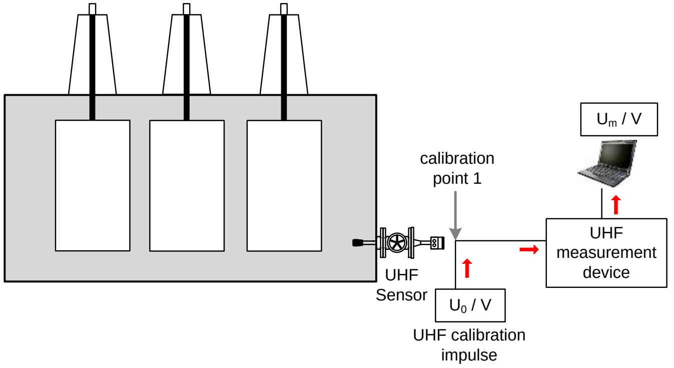

Figure 9. Calibration of measurement device and cables.

From this calibration measurement, the calibration factor K_1 can be calculated, see equation (2). K_1 compensates all losses in the cable, the inaccuracy of the measurement device and variations between different devices. The calibration impulse must contain a sufficient frequency spectrum to cover the entire measurement range.

$$K_1 = \frac{U_0}{U_m} \tag{2}$$

5.2 CALIBRATION PROCEDURE OF THE UHF SENSOR

In order to include the sensor's characteristic into the calibrated path, its AF(f) is used. 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, the frequency dependent AF(f) can be reduced to a scalar correction factor AF_S 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. An example of the simplification of the AF(f) to a mean AF_S is illustrated in Figure 10. The resulting calibration point which is shifted inside the transformer to the UHF antenna is shown in Figure 11. The resulting AF_s can be used delogarithmized as K_2 to correct time domain signals, see equation (4).

$$AF_S = \underset{300MHz \leq f \leq 1GHz}{\text{mean}} \text{AF}(f) \tag{3}$$

$$K_2 = 10^{\frac{AF_S}{20}} \tag{4}$$

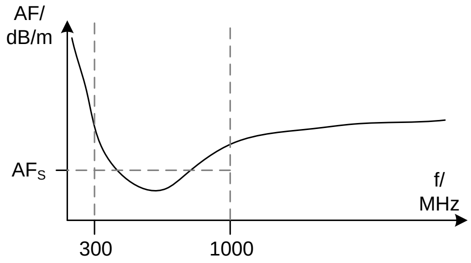

Figure 10. Example of simplifying the AF

The method of using a mean value of the frequency dependent AF(f) is only valid for broadband UHF measurement systems. If narrowband measurements are performed, the actual AF(f) at the center frequency f_{center} should be used for K_2 because the deviation between the mean AFs and the actual AF(f_{center}) could be large.

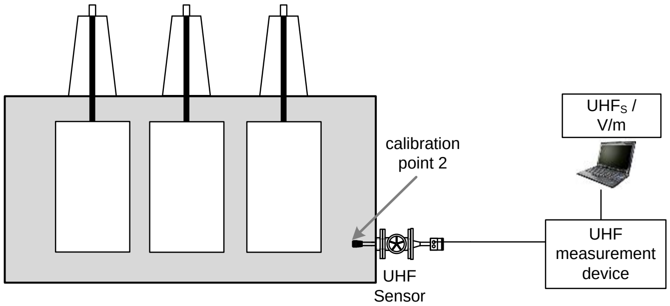

Figure 11. Calibration of the UHF sensor.

5.3 CALIBRATION PROCEDURE OF THE ENTIRE UHF MEASUREMENT SYSTEM

The complete UHF calibration factor K_{UHF} is given in equation (5).

$$K_{UHF} = K_1 \cdot K_2 \tag{5}$$

A voltage signal U_m measured with the UHF measurement system can now be corrected to a value correlated to the electric field which is radiated by a PD. This value is named "apparent UHF signal" (UHF_S), following the glossary of the electrical PD measurement: "apparent charge (q_S)". In fact, it is an apparent value because it is not directly related to the actual PD level itself.

$$UHF_S = K_{UHF} \cdot U_m \tag{6}$$

5.4 COMPARISON OF ELECTRICAL AND UHF CALIBRATION PROCEDURE

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 electrical setup (coupling capacity and quadrupole) and the measurement device can be corrected using calibration for the electric measurement (IEC 60270). A comparable calibration to compensate the influence of the UHF measurement setup including UHF sensor is achieved by the proposed method in the previous chapters. Figure 12 shows the calibration procedures as well as the transfer functions (TF) that are included into the calibrated path for electrical- and UHF-methods. In case of the UHF calibration, the sensor is included by calculation using its AF.

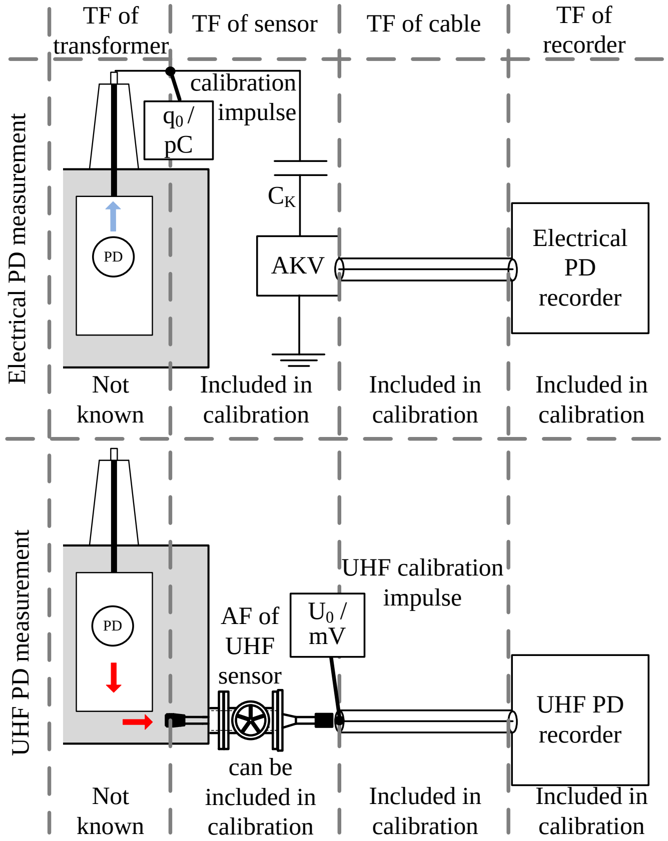

Figure 12. Comparison of PD calibration methods.

The propagation mechanisms of electrical and electromagnetic signals inside the transformer are fundamentally different and so are the attenuations of the signals. The electrical PD measurement is influenced (damped) by the inductivity of every turn and all stray capacities. 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.

In contrast to the definition of the term UHF calibration made in this contribution, "UHF calibration" is often used misleadingly as a synonym for the relation between measured UHF antenna voltage (in mV) and apparent charge (in pC) of the electrical measurement. Because this relation does not exist for complex structures such as power transformers because of the unknown propagation paths of both signal types [5], the word calibration should only be used in its original intend: ensure comparability between measurement setups of one measurement method.

5.5 PERFORMANCE CHECK

The calibration procedure does not include inside transformer attenuation, see Figure 12. Therefore, a performance check based on a second (emitting) UHF sensor inside the transformer is required at each individual transformer. A yet to be defined UHF pulse is injected into one sensor and its signal response is recorded at the second sensor. The impulse's frequency range should cover a wide spectrum of the UHF range. Therefore, a very fast rise time t_r of the pulse signal is required (typically, t_r in the range of 100 ps). In order to determine setup sensitivity the amplitude should be adjustable. Ideally, both sensors lie on the diagonal of the transformer's cross section for maximum distance. If the signal response is detectable, it could be stated, that the attenuation through the transformer is small enough to enable UHF signal measurements. Otherwise, attenuation is too high for valid measurements (e.g. due to internal electromagnetically shielding by tubes at the oil valve or by metallic deflector plates). Of course, this represents a generalization because only one specific setup for propagation paths is used as indicator for the entire transformer. Hence, this proposal has yet to be proven useful in practice.

6 INVESTIGATION ON SENSOR INSERTION DEPTH

In the following, the influence of the insertion depth on drain valve sensors is investigated using the AF as indicator. AFs measured in a GTEM-cell are compared with practical measurements at a test transformer.

6.1 INFLUENCE OF INSERTION DEPTH IN A GTEM CELL

The UHF drain valve sensor is installed at the GTEM cell using a DN50 oil valve, see Figure 13. It is tested in the following positions:

- Pos. 1: The antenna is still inside the gate valve which is an undesirable installation but does occur at practical measurements.
- Pos. 2: The antenna just reaches into the transformer's tank volume. This is the most common case for transformer installations.
- Pos. 3-5: The antenna reaches even further into the cell. These insertion depths are often not possible in practice because sufficient distance to the HV windings has to be ensured to provide save insulation.

Figure 14 illustrates the influence of different insertion depths of an UHF drain valve sensor with DN50 gate valve. Best AFs are achieved at high insertion depths, see Pos. 5. The local maximum caused by the gate valve is shifted to lower frequencies. The worst case installation at Pos. 1 increases the AF especially at frequencies $f < 1$ GHz. Additionally, new peaks occur at 1.9 GHz / 2.1 GHz and at frequencies $f > 2.6$ GHz. Hence, this position is not desired for any UHF PD measurement.

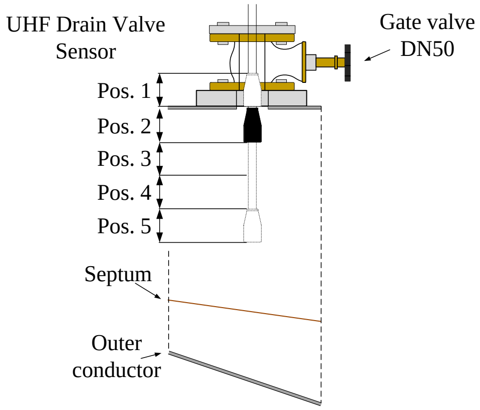

Figure 13. UHF sensor in the GTEM cell at different insertion depths.

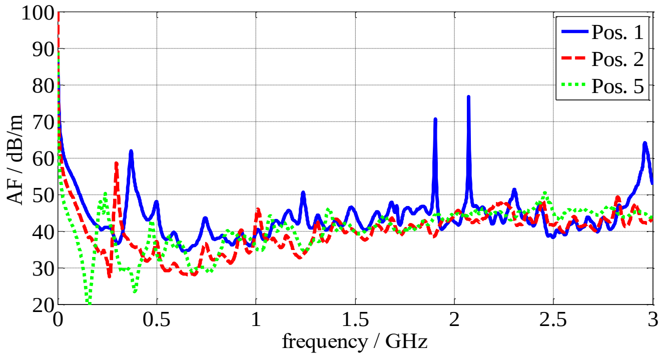

Figure 14. AF of UHF drain valve sensor measured in the GTEM cell at three different insertion depths

6.2 INFLUENCE OF INSERTION DEPTH IN A TRANSFORMER (PERFORMANCE CHECK)

The influence of the different AFs on practical PD measurements can be shown using the introduced performance check procedure. A transformer is equipped with three UHF drain valve sensors. One is used as transmitting antenna and the others are used as receiving antennas at variable insertion depths. Figure 15 presents the measurement setup.

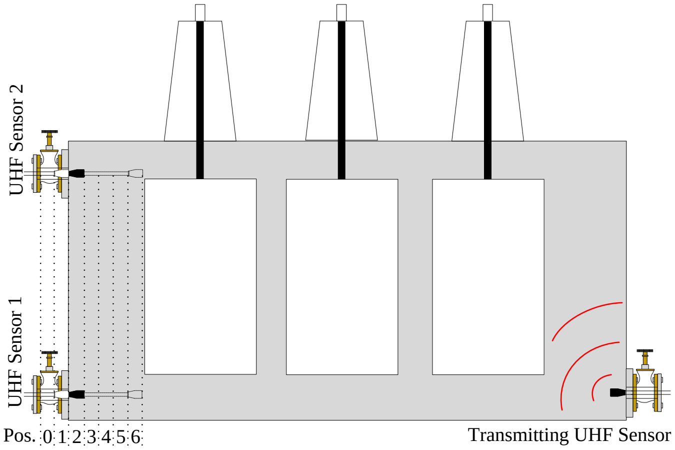

Figure 15. Transformer with three UHF drain valve sensors; one acting as transmitting antenna and two receiving sensors at different insertion depths.

In addition to the positions 1-5 tested in the GTEM cell (see Figure 13), two more positions are tested at the transformer:

- Pos. 0: the entire sensor is inside the duct of the gate valve
- Pos. 6 is at maximum insertion depth (and hence as Pos. 3-5 usually not possible in practice).

The transmitting UHF sensor emits constant pulses in the UHF range at constant insertion depth. Figure 16 shows the max. UHF amplitudes measured at the receiving sensors with a digital storage oscilloscope (DSO) with 4 GHz analog bandwidth.

No UHF signal can be detected at Pos. 0 inside the duct which acts as an electromagnetically shielding for UHF signals. At Pos. 1, which is near the transformer volume but still inside the oil valve, UHF impulses are measured with low amplitudes of approx. 20 mV. As soon as the sensor reaches into the tank volume (starting with Pos. 2), the resulting UHF signal amplitudes are approx. one power of ten higher in the range from 100 to 300 mV. The amplitude variation for positions 2 to 5 can be explained by the changing antenna geometry which leads to a changing AF. The geometry is defined by the antenna design and its distance to the ground plane which is represented by the GTEM cell's outer conductor or the transformer tank wall.

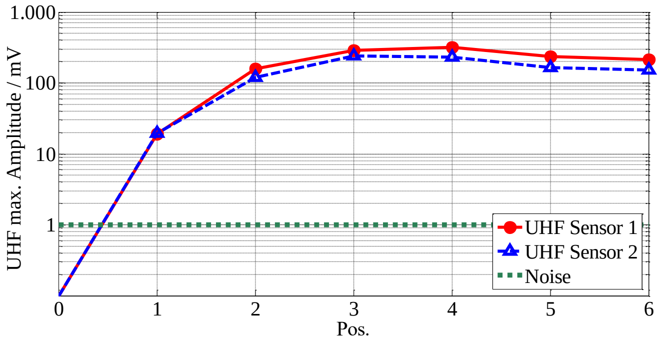

Figure 16. Measured max. UHF amplitudes of the receiving sensors at different insertion depths (Pos. 0 to Pos. 6). The detection limit of the DSO (noise floor) is plotted in green.

It is common to insert the UHF sensor just reaching into the transformer's tank volume (compare Pos. 2). The presented results support this approach. Higher insertion depths (Pos. 3 and Pos. 4) lead to minor increases of the signal amplitude but are usually not favorable at transformer installations due to the high field strengths.

7 CONCLUSION

Various types of UHF sensors are available on the market, e.g. drain valve and plate sensors. Other sensors are still in development e.g. the combined acoustic/UHF PD sensor. UHF sensors can be used for various applications at power transformers such as PD monitoring in noisy environment or as a trigger for acoustical PD localization. To become widely accepted and potentially used for acceptances test, the UHF method itself requires a calibration process, in a similar way as the calibration of the electrical measurement (according to IEC 60270). Otherwise, measurements of different UHF measurement systems cannot be compared with each other. Yet, comparability and hence reproducibility is one basic requirement for any accepted PD test method. In contrast to the electrical measurement, UHF calibration cannot cover the entire UHF measurement equipement because the UHF sensor is installed inside the transformer and therefore excluded from the path between calibrator and PD recording unit. In contrast to this, the electrical calibration includes the entire equipment.

The calibration process of the UHF method proposed in this contribution is performed by injecting a known impulse directly into the UHF measurement system as reference without UHF sensor. The influence of the sensor is included by a second step mathematically into the signal path by using the sensors antenna factor (AF). A standard setup like the presented oil-filled GTEM cell can be used to obtain the AFs of different sensors. The proposed UHF calibration procedure enables comparable measurements independent of the individual sensors, cables and measuring devices. Thus, a standardization of the UHF method can be achieved which is considered indispensable for future development of the UHF method and for definitions of UHF acceptance levels at factory and site acceptance tests (FAT and SAT).

Both, the standardized electrical and the proposed UHF calibration procedures cannot consider the physical transmission path of electrical or UHF PD signals through the active art of the transformer (this propagation is part of the device under test, not part of the calibrated measurement system). Therefore, the measured values have to be called "apparent" in both cases. In order to estimate the in-transformer signal attenuation and hence the suitability of UHF measurements at the individual transformer a UHF performance check is proposed which injects a standardized signal into a second UHF sensor ideally positioned across the transformer tank and checks if the signal can be detected at the measuring sensor. Standardized UHF reference signals for both, the described calibration (step 1) and the performance check procedure have to be defined in future research.

AF measurements in a GTEM-cell as well as practical measurements on a transformer are significantly influenced by the sensor's insertion depth. Hence, it is necessary to define a standardized insertion depth for a standardized UHF method. An insertion depth where the antenna just reaches into the transformer's tank volume is recommended because this sensor position represents a compromise between sensitivity and safety. Additional parameters should also be taken into consideration for future standardization efforts, e.g. the sensor positions.

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