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Parameters influencing Partial Discharge Measurements and their Impact on Diagnosis, Monitoring and Acceptance Tests of Power Transformers

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SUMMARY

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 on PD activity during service. This contribution compares the conventional electric method (IEC60270) and the electromagnetic method concerning their suitability for transformer surveillance. Both methods are evaluated in a test setup using a synthetic PD source with constant charge and changeable position. The main focus is on the correlation between the apparent charge of the measurement according IEC60270 in a calibrated setup and the actual charge of the source.

Concerning ultra-high frequency (UHF) PD measurements, the sensitivity of installed sensors and measurement devices are determined and evaluated. 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. The procedure requires high signal amplitudes in the UHF frequency range to enable signal transmission through the attenuated propagation path inside the transformer. Therefore, a new high power UHF impulse generator is suggested.

A calibration procedure for the 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. A characterization of UHF sensors by the antenna factor (AF) is a precondition for the 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.

KEYWORDS

Power Transformers, Partial Discharge, IEC60270, UHF, Electromagnetic, Monitoring, Calibration, FAT, SAT.

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1. INTRODUCTION

Power transformers can be considered as one of the essential equipment concerning the reliability of the electrical grid. Transformer failures lead to consequential damage with accordant costs. The reliable operation of power transformers is essential for supply 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 on- and offsite measurements. There are mainly three different ways of PD monitoring: indirectly by dissolved gas analysis (DGA) monitoring, directly by PD measurement method according IEC60270 [2] and directly by electromagnetic measurements [12] 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 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 according to IEC60270 which is required for acceptance certificates at routine testing. Therefore, the apparent charge Q_{IEC} has become an indicating factor for transformer quality.
UHF measurements base on the radiation of electromagnetic waves 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. Therefore, 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 Figure 1. Electrical signals travel through the galvanic coupling along the winding and are decoupled at the measurement capacity of the bushing (for online monitoring) or with an external coupling capacitor (not shown). Electromagnetic signals are not bound to the galvanic coupling and can radiate directly through the oil-filled transformer. Additionally, UHF PD measurements are usually shielded electromagnetically against external disturbances, e.g. corona, by the grounded transformer tank itself [5].

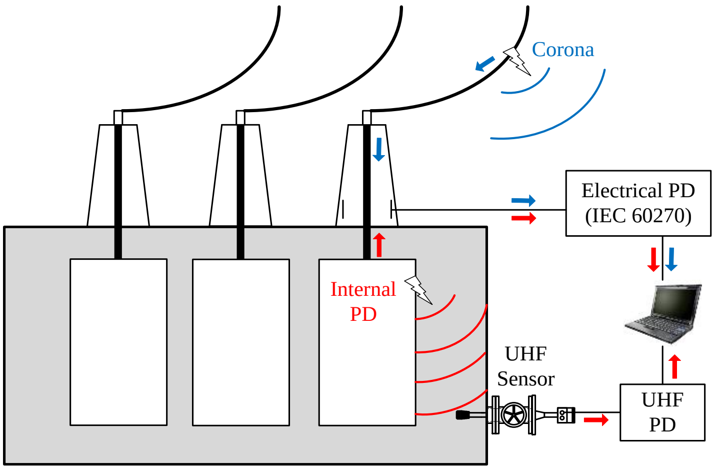

Figure 1: Signal propagation of UHF and conventional PD measurement at a power transformer with internal (red) and external PD (blue) [6]

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 to supplement electrical measurements. Basically, it lacks so far a calibration procedure which makes UHF sensors and measurement systems incomparable to each other. Due to that, the UHF technology is not so far applied as criteria for acceptance tests and is mainly used for supplement diagnostic measurements or online monitoring systems. Contrarily, for electrical PD measurement there is a calibration procedure for the ratio between capacitance of specimen and coupling capacitor available. 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.

2. ACTUAL PD LEVEL AND TRANSMISSION PATH OF PD SIGNALS IN A TRANSFORMER

The fundamental difference between the two methods is their physical values. The apparent charge level in terms of pico Coulomb (pC) of the electrical measurement is determined by integration of the recharging current. The electromagnetic radiation of the PD is measured in terms of millivolt (mV) using UHF sensors. There is always a partly unknown propagation path because both methods cannot measure directly at the defect. Thus, the actual level of PD (pC or mV) remains unknown within a power transformer. Nevertheless, a common acceptance level for the apparent charge in terms of pC has become widely accepted, especially in factory routine tests (FAT). Due to disturbances by ambient noise and existing corona discharge activities, there are certain drawbacks for the use in the field or for online monitoring purposes. In theory, both measured variables contain the same information. A linear physical relation between measured UHF antenna voltage (in mV) and apparent charge (in pC) of the electrical measurement can be demonstrated in a constant laboratory setup with simple geometry. However, it is not given for complex structures like power transformers [12].
UHF antennas measure electromagnetic emissions of PD directly in-oil inside a transformer, which acts as a “Faradys cage”. Due to the shielding effect, usually UHF measurement is advantageous concerning external disturbances. This makes it suitable for both, offsite measurement at routine testing under laboratory conditions with low ambient noise e.g. at FAT and especially onsite with usually high noise levels, e.g. after transportation and installation of transformers as a site acceptance test (SAT). These considerations make the UHF method interesting as supplement for transformer routine tests, when it´s sensitivity can be defined and demonstrated case by case.
However, some PD sources do not radiate UHF and can only be measured conventionally. Vice versa, it can also occur that electrical signals from PD, located deep in the winding, are strongly attenuated and lead to very small apparent charges which can be below noise level and may only be measured by UHF method.

2.1. Attenuation of the Propagation Paths

2.1.1. Damping in the Coupling Path of Electrical Measurement

The propagation mechanisms of electrical and electromagnetic measurements are fundamentally different and so are the attenuations of the signals. In the electrical PD measurement, the winding conductor serves as propagation path. The winding represents a RLC network with low-pass filter function [10], [12] considering its inductance and stray capacities; see the equivalent circuit in Figure 2 a). The filtering effect or damping of apparent charge signals might be identified by accurate simulations and exact geometric knowledge but can be practically regarded as unknown as well as the internal capacities at the fault location. This is illustrated by a void inside the insulation system. Figure 2 b) shows a simplified equivalent circuit of a void and an intact surrounding insulation system.

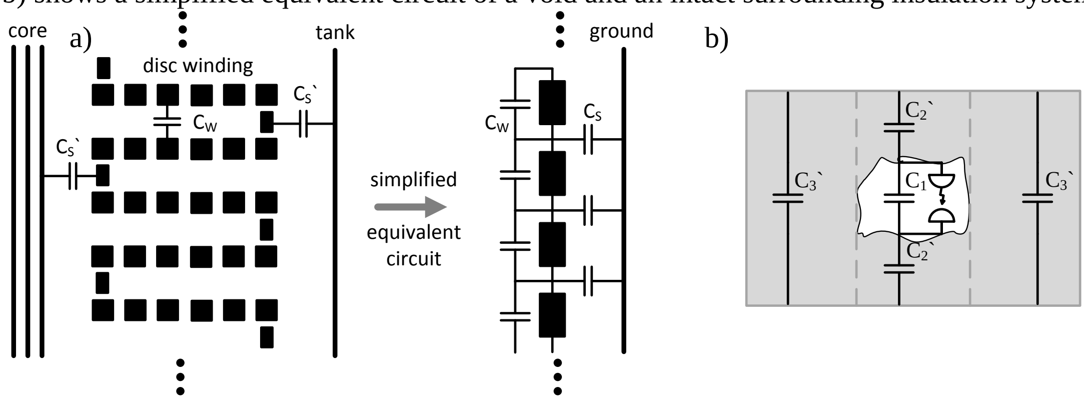

Figure 2: a) Transformer disc winding as low-pass filter for electrical PD signals
b) Internal capacitances of a void (C_1) and of the surrounding insulation material (C_2’ and C_3’) [11]

If a PD occurs, the capacity C_1 of the void is partially recharged from the inner capacities C_3’ of the intact insulation and partly from the external coupling capacitor. Only the recharging current of the connected coupling capacitor can be measured. As both the location (and hence the coupling path) and the dimension of the defect are not known, the ratio between the capacitances C_1, C_2' and C_3' is not known which makes the internal PD recharging current incalculable.

2.1.2. Damping in the Propagation Path of UHF Measurement

Electromagnetic signals in the UHF range propagate in the entire volume of the transformer through oil and pressboard, independent from the galvanic coupling path. Nevertheless, the electromagnetic wave is attenuated and can also be reflected by metallic parts. The entire attenuation of the electromagnetic propagation inside a transformer is relatively low; approximately 2 dB per meter for transformer oil [12]. With distant sources, the electromagnetic waves propagate through an unknown system before they reach the sensor. Therefore, a calculation of the actual PD value is also not possible, similar to the electrical measurement.

2.2. Actual vs. Measured PD Level and the Influence of Calibration on the Apparent Charge

The aforementioned influence in the propagation path raises the question of the difference between the PD signals measured by both methods and the original signal of the source. Therefore, the general damping along the propagation path was shown in the chapter before for both, electrical and UHF measurement. Ideally, calibration eliminates all influences of the propagation path within the measurement setup. By definition, the calibration point represents the connection between measurement setup and the device under test (DUT). The discrimination can be done by the evaluation of four questions:

- Which part of the propagation path can be included in the calibration procedure?
- Which factors influence the measurement readings?
- Which parts are not included into calibration procedure?
- Which factors influence those parts?

Applied to transformer PD measurement, calibration can therefore only include the signal path between the signal recorder and the point where the sensor is attached to the transformer. For the electrical measurement, the connection point is the bushing where a reference signal can be applied. By feeding in a known charge pulse q_0 as close to the DUT as possible, the ratio of the measured charge q_m to the known impulse q_0 is determined and adjusted by a calibration factor. This calibration determines and compensates the ratio of coupling capacitance C_K and the capacitance of the DUT C_T. The measured value after calibration is known as apparent charge q_s. Therefore, actual and apparent charge of PD signals near to the calibration point (e.g. at the lead exit) are almost similar. PD signals which originate farther from the calibration point are influenced by the inside transformer propagation path which is not included into the calibration procedure. As mentioned before, those parameters are strongly linked to the geometric design of each winding and likely to be unknown.
As the UHF method is applied in increasing numbers, there is also a demand to calibrate UHF measurement setups in a similar way like the conventional electric measurement in order to ensure comparability between different UHF measurements. In principle, the signal path which can be calibrated is very much the same as within electrical measurement: between the sensor (in this case the UHF antenna) and the recording device. Calibration itself is different: it includes the influence of the sensor inside the transformer by its frequency dependent antenna factor. The factor strongly depends on the geometry formed by the sensor's antenna and the ground plane represented by the tank wall. Hence, the antenna factor has to be measured and then included into the calibration procedure. This makes UHF calibration more complex than for the electrical measurement and the appliance of a calibration signal alone is not sufficient. A detailed consideration of UHF sensor calibration is provided in chapter 3.
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. However, a calibration of UHF measurement does not draw this physical relation between the UHF antenna voltage and the apparent charge. This connection might exist for specific arrangements but can be regarded as non-existent for complex structures like power transformers [12].

2.3. Influence of PD Location and Frequency Range on the Apparent Charge and the UHF Signal Amplitude

The influence of the location of PD on its electrical and UHF signals is determined using a laboratory setup. A cylindrical steel tank is equipped with a winding and a stable, synthetic PD source which is adjustable in height along the winding. The entire winding is on high voltage potential, it can be connected by the upper or the lower winding exit to HV potential. For UHF measurements, 5 UHF antennas are inserted into to tank: 4 sensors attached through DN80 drain valves and one UHF plate sensor welded directly on the top (sensor 5). Figure 3 a) shows the experimental setup. The synthetic PD source consists of two copper plates connected through a capacitor and a gas-filled discharge tube (GDT). One copper plate is galvanically connected to ground and the other couples to the HV winding through the stray capacity [11]. It provides a reproducible, phase stable, constant charge conversion. The constant original PD charge is 1000 pC and it emits constant electromagnetic radiation and hence can be used as UHF PD source.

During the experiment, the position of the PD source is changed and the distance between top of the tank and source is stepwise increased. The electrical measurement is calibrated for each frequency range used, details see below. The broadband UHF measurement does not require recalibration but needs knowledge of the different sensors' antenna factors, see chapter 3.

The measured antenna voltage of each sensor at changing source location is shown in Figure 3 b). The signal for sensors 1 and 2 decreases if the distance to the source increases (note that sensor 1 is at the bottom of the tank) as damping is approximately 2 dB/m in a uniform propagation path. Due to the geometry's complexity introduced by the tank design, the propagation path damping differs from linear damping depending on the sensor position, see sensors 3 and 4. One theory states that not the PD source itself radiates the electromagnetic wave, but the surrounding structure, e.g. the winding acts as the active transmitting antenna [12]. Hence, propagation changes at each PD position by the influence of the changing emitting antenna formed by the winding and the surrounding structure.

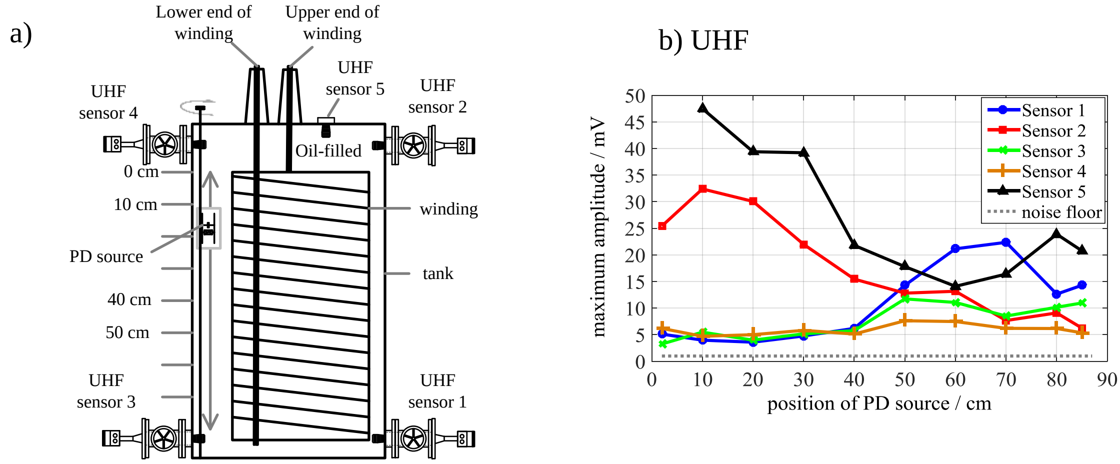

Figure 3: a) Test setup for both electrical PD measurement (IEC60270) and UHF measurement b) maximum measured UHF levels of UHF sensors 1-5 [11]

The electrical measurement is performed according to IEC60270. Two frequency ranges are used:

- IEC60270 broadband: f_m = 250 kHz, Δf = 300 kHz
- IEC60270 narrowband: f_m = 1 MHz, Δf = 30 kHz

Apparent charges are measured using a calibrated system either on the upper or the lower end of the winding. The results are shown in Figure 4 a) (broadband) and Figure 4 b) (narrowband). The black line shows the original PD charge of the source at 1000 pC.

Determining the broadband measurement, several findings can be stated: Both, the upper and the lower end of the winding measurement show a strong dependency considering the distance between the respective calibration point and the source (coupling path) despite the constant source. In addition, the correlation between distance and apparent charge is not trivial; there is no monotone or linear dependency. At particular positions the apparent charge decreases strongly (e.g. at 80 cm for the upper winding measurement and at 10 cm for the lower winding measurement). The upper winding measurement shows a local minimum of the apparent charge at 60 cm, whose corresponding effect cannot be found at the lower winding measurement. Concluding, the electrical propagation is affected by non-linear damping and is not reciprocal. The provided measurements show no correlation between the measured data. The evaluation of the narrowband measurements in Figure 4 b) show a comparable behavior of upper and lower winding measurements.

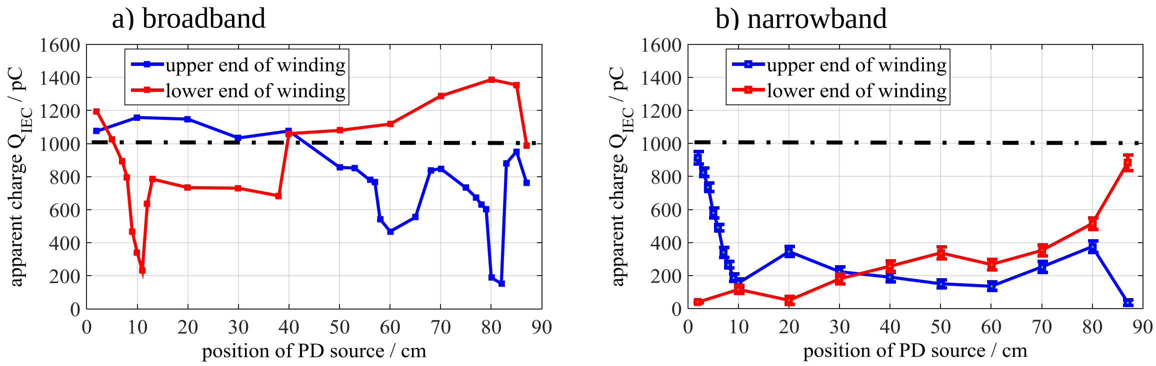

Figure 4: Apparent charge of electrical PD measurement at upper and lower end of winding; dotted line: Actual charge of the source [11]

The measured apparent charge strongly decreases within small distances between source and calibrated measurement point (up to approx. 10 cm). At larger distances the apparent charge stays low but does not show any monotone or linear dependency.
Compared to the broadband measurement at lower frequencies, the narrowband measurement shows a more expected behavior. Nevertheless, both results come to the same conclusion for the practical PD measurement with unknown source position: the measured apparent charge cannot be correlated with the actual charge of the source. Usually, the measured values underestimate the actual PD charge but within broadband measurements an overestimation is also possible.
Those findings have to be kept in mind when referring to PD acceptance criteria during FAT testing of transformers.

3. 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, see chapter 2
- 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 according to IEC60270. A correction factor to compensate the UHF sensor's influence can be achieved and will finally be explained in chapter 5. 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 [12]. Because of the different permittivities ($\varepsilon_{r,air} = 1$, $\varepsilon_{r,oil,\ 50\ Hz} \approx 2{,}3$), 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 [13].

3.1. UHF Sensor Characterization

The antenna sensitivity depends on its design in relation to the electromagnetic wavelength. Antennas are described by different characteristics, e.g. by the antenna gain or the antenna aperture. For antennas which are not defined by a physical area, such as monopoles or dipoles, the effective length l_{eff}, or the antenna factor AF can be used which is the following:

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

where $U(f)$ is the voltage at the antenna terminals and
$E(f)$ is the electric field strength at the antenna.

An appropriate special designed oil-filled GTEM cell [6,13] is used for the evaluation of the antenna sensitivity, shown in Figure 5 a) and b).

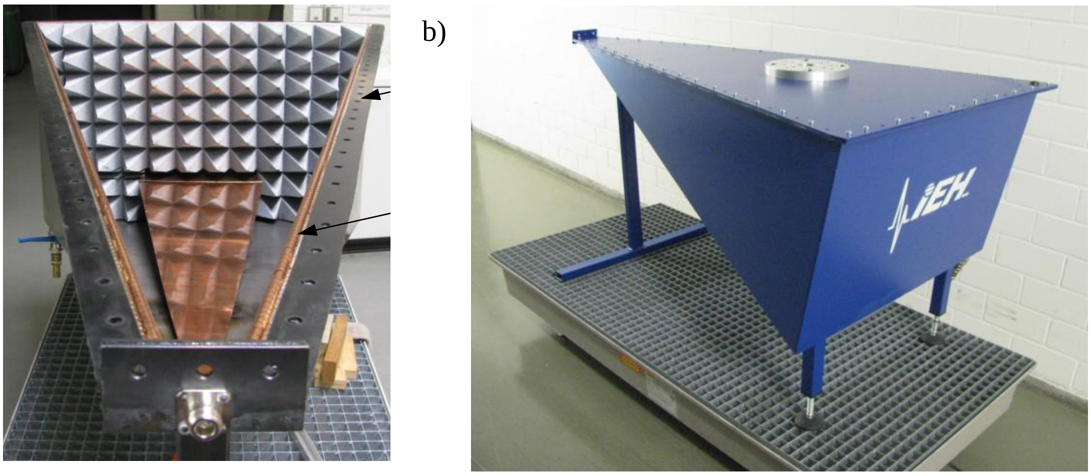

Figure 5: a) GTEM cell internal view with absorbers and septum before oil filling
b) GTEM cell external view

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 provides a homogeneous electric field distribution E_{hom} and an orthogonal magnetic field of the TEM wave, ideally. In addition, the electric field strength E_{hom} in the test volume has to be known for AF calculation of the EUT.

3.2. Antenna Factor Measurement with GTEM Cell

The AF of a UHF sensor can be determined using a transmission factor (S_{21}) measurement, see Figure 6 a) and b). 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 like in the later field measurements; here an insertion depth of 50 mm from tank wall is used.

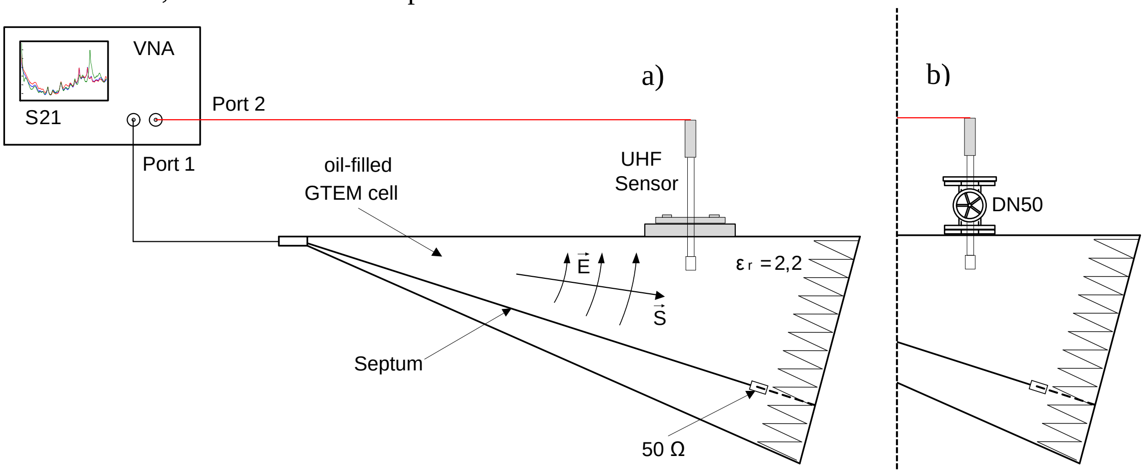

Figure 6: Transmission measurement (S_{21}) for AF determination
a) UHF sensor direct mounted to the cell without oil valve
b) UHF sensor installed via DN50 oil valve to the cell

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 S_{21} 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 Figure 7.

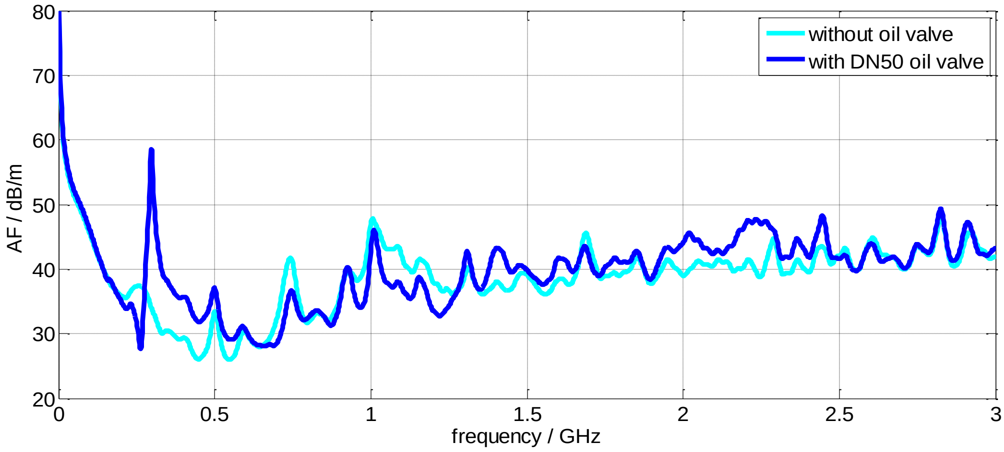

Figure 7: Antenna factor (AF) of UHF sensor measured in GTEM cell
Light Blue curve: UHF sensor direct mounted to the cell (shown in Figure 6 a))
Dark Blue curve: UHF sensor installed via standard DN50 drain valve to the cell (shown in Figure 6 b))

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 sensors AF is not negligible like the curves in Figure 7 show. The highest influence of the valve occurs at approx. 300 MHz (see resonance). Compared to a real transformer, the GTEM cell characterization measurement only considers the influence of the sensor and can therefore be regarded as first step reaching a calibration procedure.

4. PERFORMANCE CHECK PROCEDURE

The first approach to include the internal UHF transmission path is the performance check, where an UHF pulse is fed into one sensor and measured by a second sensor (and further installed sensors). If the sensors are on opposing sides of the transformer as shown in Figure 8, this performance check procedure includes the whole signal path through the transformer [12], [14]. It is not used as a calibration of the measurement system but can be used to prove that the system is able to measure electromagnetical waves emitted by PD inside the transformer. In the case of steel plates in front of the UHF sensor or a standpipe mounted to the oil valve where a UHF sensor is installed, the antenna is electromagnetically shielded. Hence a measurement system will not be able to measure UHF PD signals from inside of the transformer and the performance check will fail.

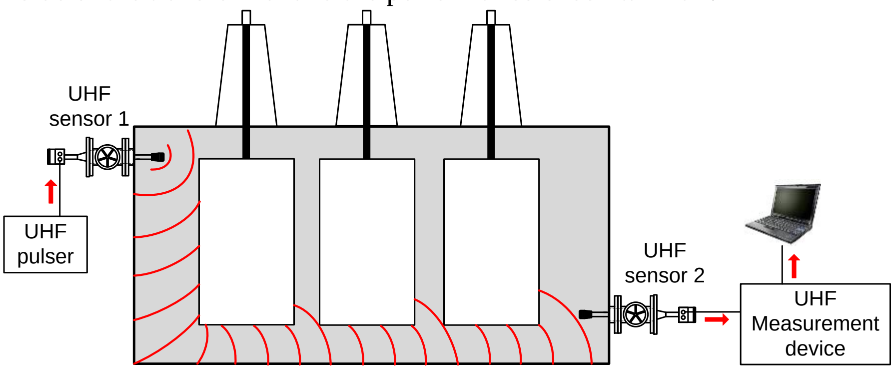

Figure 8: Performance check of UHF PD measurement

4.1. Experience with Impulse Generators at Large Power Transformers

A UHF performance check should be done when an UHF measurement and/or monitoring system is installed. This procedure is normally done with an UHF pulse generator, designed for UHF sensitivity checks in GIS systems [3] with an approx. maximum amplitude of $\hat{U}_{\text{pulse}}$ =50...60 V (in 50 Ω domain). The impulse form can be seen in Figure 9 a). Experiences with small transformers with respectively shorter propagation paths and accordingly lower damping of signal energy showed that amplitudes are appropriate and performance checks can be performed successfully. Larger power transformers with higher distances between the UHF sensors often provide higher signal attenuation and as a consequence signals strength at the second (measuring) sensor is below noise level. Hence, the UHF performance check fails because the signal does not reach the measuring sensor and therefore cannot give information about the sensors sensitivity.

Due to the lack of state of the art UHF impulse generators with higher amplitudes $\hat{U}_{\text{pulse}}$, a high power pulse generator normally used for EMI/RFI/EMC-applications is tested at a large power transformer. Its amplitude is approx. $\hat{U}_{\text{pulse}}$= 250 V (in 50 Ω domain), see Figure 9 b). The resulting impulse power is about 1,25 kW. Nevertheless, a performance check failed at the same large power transformer from the previous test.

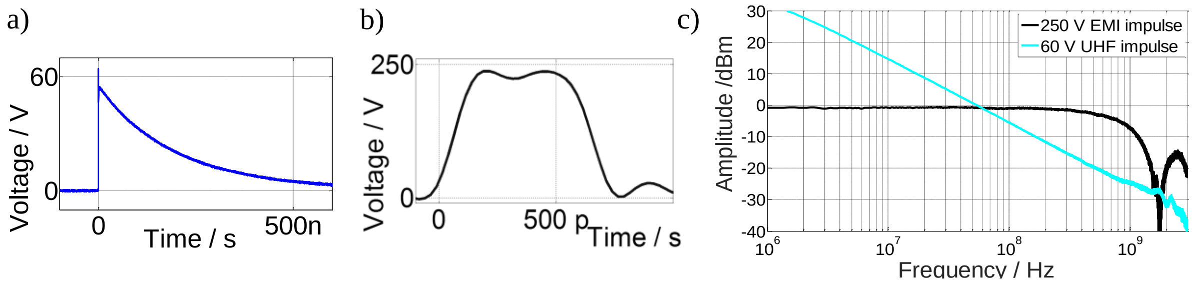

Figure 9: a) 60 V impulse of UHF impulse generator
b) 250 V impulse of EMI impulse generator
c) both impulses in frequency domain

4.2. Investigation on Transmission Characteristic of Power Transformers

The impossibility to perform a performance check at large power transformers raises the question of the frequency response of the propagation path. Therefore, two UHF sensors are installed at a power transformer and the transmission factor S_{21} is measured using a VNA in the frequency range from 300 kHz to 3 GHz. Figure 10 a) and b) represent the measurement setup and the measurement results.

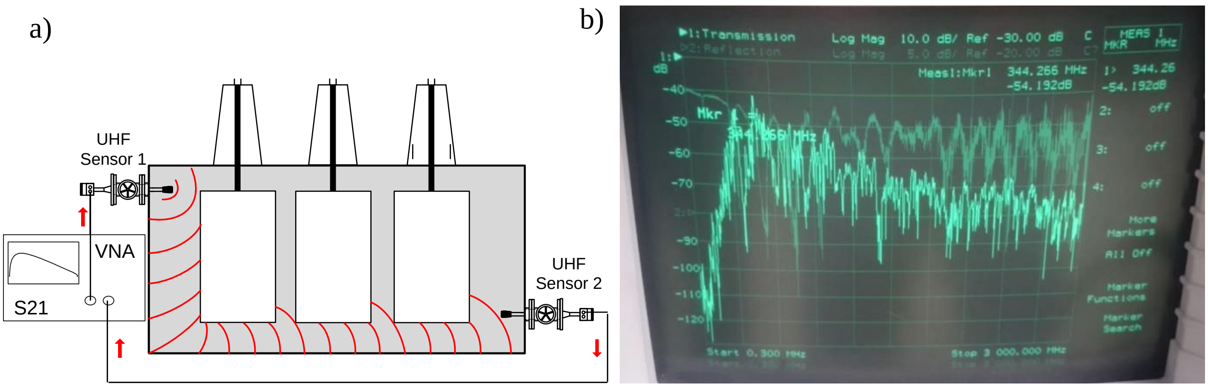

Figure 10: a) Transmission measurement from UHF sensor to UHF sensor through a transformer
b) Transmission factor S_{21} measurement through a transformer

The transmission measurement has the same shape comparable to the AF (or rather two times the AF) of the used UHF sensors. This confirms that the AF of a UHF sensor measured in the GTEM cell is valid for the sensor inside the transformer. The transmission with lowest damping occurs at a frequency range from approx. 300 to 600 MHz. Additionally, the influence of the used oil valves can be seen at the resonance at around 300 MHz (compare to AF with drain valve in Figure 7). With this information, a requirement for impulse generators for UHF performance check can be defined. It needs higher signal power in the frequency range where the UHF sensors have the highest sensitivity approx. 300 to 600 MHz.

4.3. Recommendation for UHF Impulse Generator for Large Power Transformers

The impulses shown in time domain in Figure 9 a) and b) are transferred in frequency domain in Figure 9 c). The 250 V EMI pulse generator provides higher amplitude (between 20 dB and 30 dB) than the 60 V UHF pulse generator in the frequency range from 300 MHz - 600 MHz. Therefore, the EMI impulse seems to be more suitable for this application. A new very high power UHF impulse generator is in development in order to enable UHF performance checks at large power transformers which provides high impulse amplitude in 50 Ω domain and flat spectrum up to several 100 MHz. The high bandwidth requires very short rise times $\tau_{rise} \leq 100$ ps.

5. UHF CALIBRATION PROCEDURE 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 the previous chapters. A simplified AF can then be included in the calibration procedure of UHF measurement systems.

5.1. 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 Figure 11.

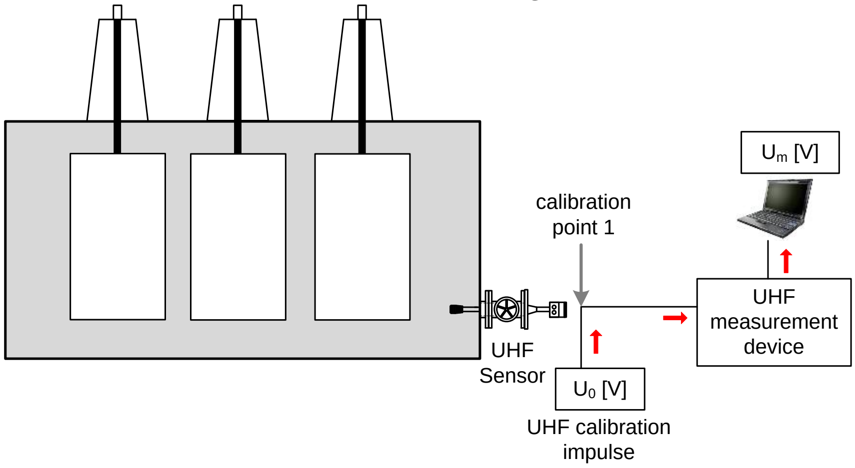

Figure 11: Calibration of measurement device and cables

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

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

5.2. Calibration Procedure of the UHF Sensor

In order to include the sensor's characteristic into the calibrated path, its AF(f) is required. Actual insertion depth has to be the same during AF determination and 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.

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

The resulting AF_s can be used in its delogarithmized form K_2 to correct time domain signals.

$$K_2 = 10^{\frac{AF_S}{20}} \qquad (4)$$

Figure 12 shows an example of simplifying the AF(f) to a mean AF_S and the new calibration point which is shifted inside the transformer to the UHF antenna.

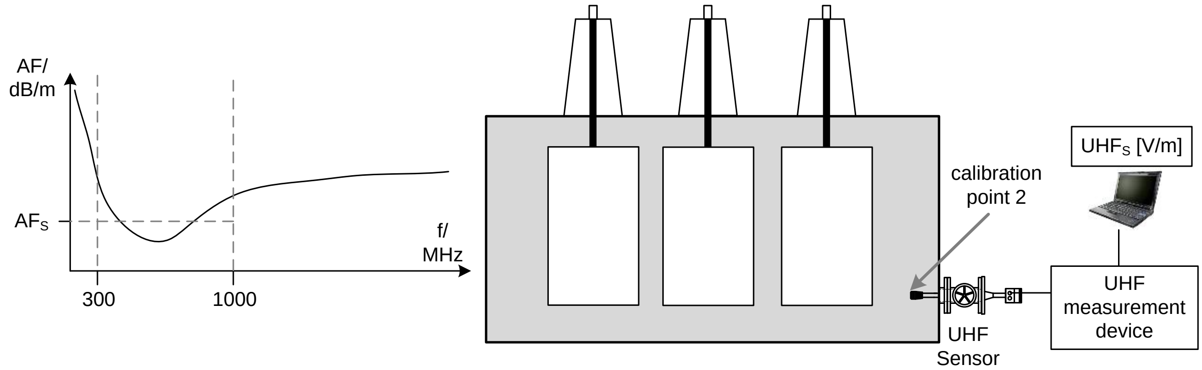

Figure 12: Calibration of the UHF Sensor

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 at the used center frequency should be used for K_2.

5.3. Calibration Procedure of the entire UHF Measurement System

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

$$K_{UHF} = K_1 \cdot K_2 \qquad (5)$$

An impulse U_m measured with the UHF measurement system can now be corrected and a value correlated to the electrical field emitted of a PD is displayed. This value can be called “apparent UHF signal” (UHF_S) like “apparent charge (q_S)” of the electrical PD measurement. It is called apparent because it is not directly related to the actual PD value itself but comparable between different measurement systems (including UHF sensors, cables and measuring devices) due to its calibration.

$$UHF_S = K_{UHF} \cdot U_m \qquad (6)$$

5.4. Performance Check

A performance check always has to be done (see previous chapter) because calibration procedure does not demonstrate performance of the antenna to electromagnetical signals from inside of the transformer. Although “calibrated”, PD measurement might be impossible due to internally electromagnetical shielded sensors by e.g. tubes. (the same phenomena might occur at the electrical “calibrated” measurement set-up in the very unlikely case of an internally not connected bushing.)

5.5. 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 (in pC) needs to be treated with caution, this contribution shows that this connection 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. The following Figure 13 compares in conclusion both calibration procedures and shows 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). The propagation mechanisms of electrical and electromagnetic signals inside the transformer are fundamentally different and so are the attenuations of the signals.

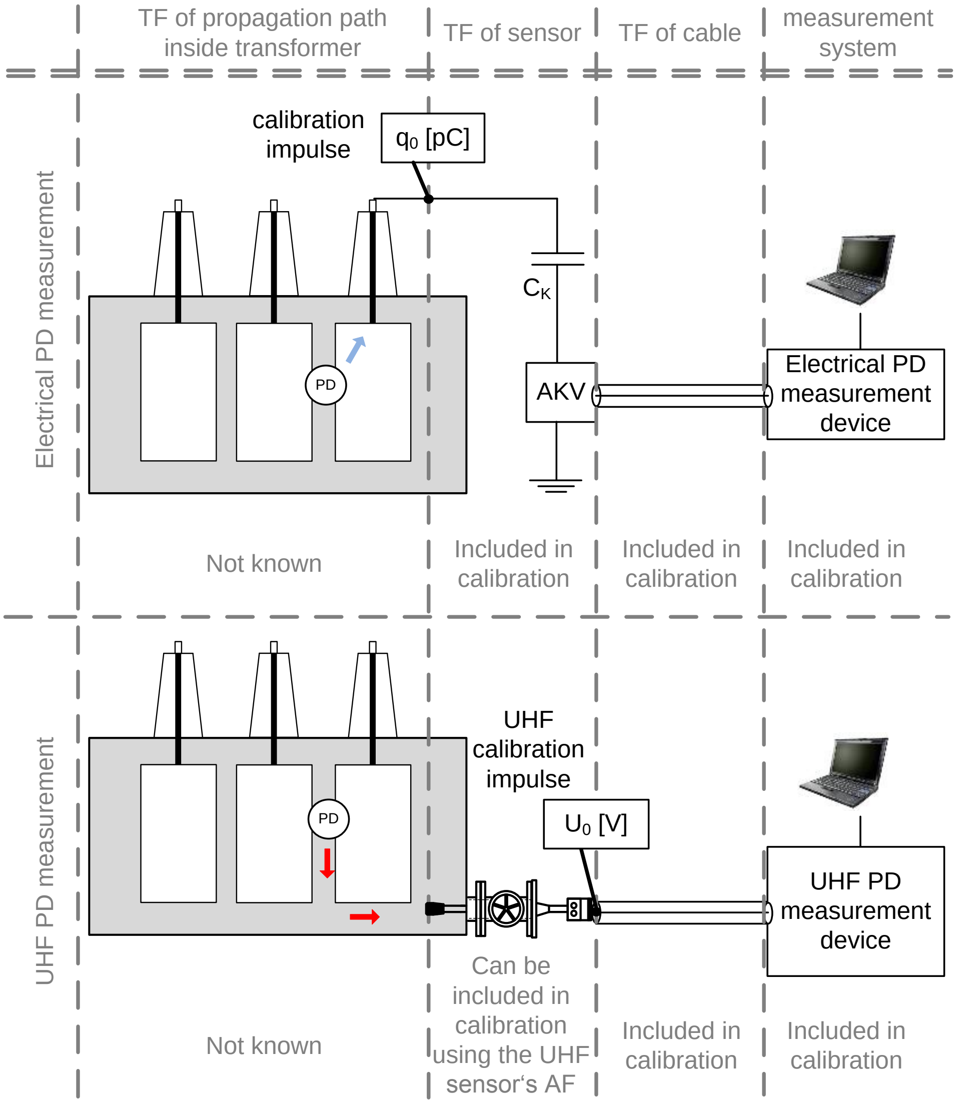

Figure 13: Comparable calibration achievements of electrical and UHF measurements

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.

6. CONCLUSION

The comparison of electrical and UHF PD measurement methods shows that the detailed propagation path and its damping effects inside the transformer remains unknown in both cases. The advantage of the conventional electrical method to the UHF measurement method is its calibration procedure which eliminates effects of the propagation path between the connection point at the transformer and the measurement device (mainly the coupling capacity and the quadrupole). The signal propagation inside the transformer remains unknown. As experiments show, the unknown path does have a significant influence on the apparent charge as well as the chosen frequency range. Therefore, the calibrated apparent charge cannot be related to the actual charge or energy conversion of internal PD source inside the winding.
A performance check is still necessary for UHF measurements (as well as electrical measurements) but cannot always be performed on large power transformers as shown in onsite measurements using

state of the art UHF impulse generators. VNA measurements at a power transformer show best transmission factors with lowest attenuation in the range approx. 300 MHz - 600 MHz (AF of used sensors included). Therefore, a very high signal power UHF impulse generator with flat spectrum up to this frequency range is recommended and currently developed.
A characterization of UHF sensors is available by introducing a frequency dependent AF which is determined in full UHF range using an oil-filled GTEM cell. The now known sensor characteristics allow a calibration procedure of the UHF method which is proposed in this contribution for the entire UHF measuring systems. This calibration procedure is essential for comparable UHF measurements independent of the used sensors, cables and measuring devices. Thus, also the 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.

BIBLIOGRAPHY

[1] J. Fuhr, „Procedure for Identification and Localization of Dangerous PD Sources in Power Transformers," *IEEE Transactions on Dielectrics and Electrical Insulation,* No. 5, Vol.12, 2005.

[2] International Electrotechnical Commission (IEC), „IEC 60270 High Voltage Test Techniques - Partial Discharge Measurements," Geneva, Switzerland, 2000.

[3] CIGRE TF 15/33.03.05, „PD Detection Systems for GIS: Sensitivity Verification for the UHF Method and the Acoustic Method," *International Council on Large Electric Systems, Electra,* No. 183, 1999.

[4] CIGRE WG A2.27, „Recommendations for Condition Monitoring and Condition Assessment Facilities for Transformers," in *Cigre Brochure 343*.

[5] M. Judd, „Partial Discharge Monitoring for Power Transformers Using UHF Sensors Part 2: Field Experience," *IEEE Electrical Insulation Magazine,* No.3, Vol. 21, 2005.

[6] S. Tenbohlen, M. Siegel, M. Beltle, M. Reuter, „Suitability of Ultra High Frequency Partial Discharge Measurement for Quality Assurance and Testing of Power Transformers," in *CIGRE SC A2 & C4 Joint Colloquium*, Zurich, Switzerland, 2013.

[7] S. Coenen, „UHF and Acoustic Partial Discharge Localisation in Power Transformers," in *International Symposium on High Voltage Engineering (ISH),* Hannover, Germany, 2011.

[8] CIGRE WG D 1.33, „Guidelines for Unconventional Partial Discharge Measurements," International Council on Large Electric Systems, Paris, France, 2010.

[9] M. D. Judd, „Power Transformer Monitoring Using UHF Sensors: Installation and Testing," in *IEEE Intemational Symposium on Electrical Insulation,* Anaheim, USA, 2000.

[10] S. Okabe, G. Ueta, H. Wada, „Partial discharge signal propagation characteristics inside the winding of gas-filled power transformer - study using the equivalent circuit of the winding model," in *IEEE Transactions on Dielectrics and Electrical Insulation*, 2011.

[11] M. Siegel, S. Tenbohlen, Comparison between Electrical and UHF PD Measurement concerning Calibration and Sensitivity for Power Transformers, International Conference on Condition Monitoring and Diagnosis (CMD), Jeju, Korea, 2014.

[12] S. Coenen, Measurements of Partial Discharges in Power Transformers using Electromagnetic Signals, Dissertation Universität Stuttgart, Books on Demand GmbH, ISBN 978-3-84821-936-0, 2012.

[13] M. Siegel, S. Tenbohlen, Design of an Oil-filled GTEM Cell for the Characterization of UHF PD Sensors, Internat. Conference on Condition Monitoring and Diagnosis (CMD), Jeju, Korea, 2014.

[14] S. Meijer, E. Gulski, J. Smit, H. Reijnders, „Sensitivity Check of UHF PD Detection on Power Transformers," in *IEEE International Symposium on Electrical Insulation*, Indianapolis, USA, 2004.