# Design of an Oil-filled GTEM Cell for the Characterization of UHF PD Sensors

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Abstract— Well known local failures in power transformers are partial discharges (PD) in the electric insulation. Continuous deterioration over time increases the defect which finally can lead to a breakdown of the entire insulation. The importance of PD measurement is accommodated by standardized electrical measurement according to IEC 60270 [1] which is required for acceptance certificates at routine testing. Therefore, the apparent charge Q<sub>IEC</sub> has become an important value for transformer quality. Since a couple of years, alternative measurement methods for PD are used. Originally developed for gas insulated systems [2], ultra high frequency (UHF) measurement found its way into transformer diagnosis over the last years [3]. To become an accepted quality factor, UHF has to be proven a reliable testing method, which can complement against electrical measurements. Therefore, the general physics of UHF PD has to be considered at first. Ultra-high-frequency antennas measure electromagnetic emissions of PD directly in-oil inside a transformer. It becomes apparent, that usually UHF measurement is advantageous concerning external disturbances [4], which makes it suitable for both, offsite measurement at routine testing under laboratory conditions with low ambient noise and onsite with usually high noise levels, e.g. after transportation and installation of transformers. These considerations make the UHF method interesting as supplement for transformer routine tests. Therefore, a sensor calibration or at least a validation of its sensitivity is required [5], comparable to the electrical measurement. To provide profound knowledge of the equipment, the antenna factor (AF) of the UHF sensor needs to be determined under inside-transformer conditions. To meet these conditions, an oil-filled GTEM cell is required for correct permittivity. This contribution shows the design of a Gigahertz-Transversal-Electro-Magnetic Setup (GTEM cell) for the determination of the UHF sensor's AF. Correction factors can then be introduced to minimize measurement errors and to establish better comparability of different UHF sensors. Hence, a standard test setup can be defined.

Keywords— Power Transformers, Partial Discharge (PD), UHF PD Measurement for Diagnosis and Monitoring, Routine Test, Antenna Factor, oil-filled GTEM cell

# I. INTRODUCTION

Power transformers can be considered one of the essential equipment concerning the reliability of the electrical grid. Transformer failures lead to consequential damage with accordant costs. Reliable operation of power transformers is essential for supply security. Damages to the insulation of a power transformer, like local defects, must be recognized at an early stage [6]. Different diagnostic methods have been established to meet the deriving demands for on- and off-site measurements. Electrical PD measurement found its way into

standard testing according to IEC 60270 [1]. Within the last decades, alternative measurement methods for PD have arisen. Originally developed for gas insulated switchgears (GIS) [2], ultra high frequency (UHF: 300 MHz – 3 GHz) PD measurement is also used in power transformers' diagnosis [3]. UHF has been established as a trigger for acoustic PD localization [7] and for onsite/online diagnostic PD measurements [8] and seems to be suitable for on-line PD monitoring [5]. Because UHF PD measurement is shielded electromagnetically against external disturbances, e.g. corona, by the grounded transformer tank itself, UHF usually is advantageous concerning on-site PD measurements, as seen in Fig 1.



Fig. 1. Power Transformer with electrical and UHF PD measurement

These features suggest the method for different applications, e.g. comparison of low noise offsite measurement with high noise levels online (after transportation and installation).

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

- 1. the type and actual level of the PD source
- 2. the signal attenuation in the coupling path
- 3. the sensor sensitivity
- 4. 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 acc. to IEC 60270. Although the actual PD charge cannot be estimated [9] because of the unknown signal path attenuation and unknown ratio of internal capacitances, calibration allows the introduction of apparent charge as an acceptance level. Hence, electric measurement became suited for routine tests. For the UHF method a correction of sensor influence can be achieved, too. To determine 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 different permittivity the AF measured in air does not apply to transformer oil, or at least needs to be shifted in frequency range to meet different wave propagation speeds. Furthermore, the full bandwidth of UHF sensors cannot be tested with conventional TEM cells. It becomes apparent, that the AF needs to be determined direct in oil at full UHF frequency range. To meet these conditions, an oil-filled Gigahertz-Transversal-Electro-Magnetic Setup (GTEM cell) is required.

## II. 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 antenna gain is often specified by the effective length  $l_{eff}$  or the antenna factor AF which is defined for a receiving antenna as

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

where U(f) is the voltage at the antenna terminals and E(f) is the electric field strength at the antenna. The effective length is defined by the inverse antenna factor. For the evaluation of the antenna sensitivity a special setup is necessary with no external disturbances and no internal reflections of electromagnetic waves. Therefore, a special equipped EMC absorber room can be used or a GTEM-cell [11], shown in Fig. 2. A GTEM cell is an expended coaxial conductor, where a defined electromagnetic field can be applied to an equipment under test (EUT) without interference from the ambient electromagnetic environment.



Fig. 2. Schematic of test bed for UHF antennas using a GTEM cell

In the cell a test volume is defined in which measurements take place. In this volume the TEM wave has to be close to ideal, meaning a homogeneous electric field distribution and an orthogonal magnetic field. Also, the electric field strength has to be known. This can be achieved by either measurement using a field probe and/or field simulations.

## III. OIL-FILLED GTEM CELL DESIGN

For UHF-antenna measurement the cell's test volume needs to be as large as possible. Therefore, the h/d-ratio is chosen to 0,75. The remaining w/a-ratio is used as variable parameter to adjust the cell's wave impedance, see Fig. 3.



Fig. 3. Change of u/d and w/a-ratios over GTEM cell length in z direction

## A. Wave Impedance

To avoid reflections at both the input and the termination the entire cell has to operate in 50  $\Omega$  domain. Therefore, its wave impedance Z has to be adjusted to meet 50  $\Omega$ . Z is defined by the per-unit-length length parameters given by the equivalent circuit of an infinitesimal short line element: the series inductance L', the series resistance R' and the conductance G' and capacity C', both to connected to ground. In this setup, both ohmic components R' and G' can be neglected due to the low electrical resistivity of a copper septum and the extremely low conductivity of the oil-filled cell. L' and C' has to be estimated for every per-unit-length parameter of the GTEM cell. Both are defined by the line element's cross-section geometry. All parameters are shown in Fig. 3 left side, where d represents the height of the crosssection, h is the height of the septum in the cell, u is the septum thickness and w its width. If the thickness u is very small compared to the cell height d, u becomes negligible. The simplification is not valid for the inlet of the cell, called apex, if the entire septum is of constant thickness due to production. Therefore, the apex is considered separately from the rest of the septum. The cell's wave impedance Z can be determined using analytic approximating methods or numeric simulations as field solving algorithms like the finite element method (FEM).

#### B. Analytic Approximation

First, an approximation method for the estimation of the capacitance of a rectangular coaxial transmission line with an infinitely thin and vertically offset septum according to [12] is used. As the applied approximation considers the inner conductor as infinitesimal thin line (u = 0) it is not suited for the apex impedance estimation [13].



Fig. 4. Line impedance Z of the oil filled GTEM cell at 3 different septum height to cell height (h/d) ratios and varying septum width to cell width ratio (w/a)

Fig. 4 shows the calculated impedance Z depending on the septum width to cell width ratio (w/a-ratio) at three different heights of the septum. As Fig. 4 indicates, the line impedance can be kept constant at any chosen cross-section if the geometric properties of the cross-section cell along the cell's elevation remain constant. For the oil-filled GTEM-cell with fix h/d-ratio = 0.75 the septum has to meet a w/a-ratio of approx. w/a = 0.4. Because u is constant over the cell length and not zero, this approximation is not used for manufacturing of the cell and is replaced by a more accurate numerical model.

# C. Numerical Model

Besides the analytic model a numeric model solved by a FEM field solver is used to calculate the wave impedance of the oil filled GTEM cell. Since the cross-section and thus the cell's wave impedance is independent of the length, it is sufficient to perform a 2D simulation for the electric and magnetic field distribution of cross-sections. Using the resulting simulated electric and magnetic field energy the capacitance C' and inductance L' can be calculated. Assuming a lossless septum, the wave impedance is calculated with Cand L'. Fig. 5 shows the dependency between wave impedance and w/a-ratio at three different cross-sections from Fig. 3 which differ in the u/d-ratio at constant h/d ratio. Its influence is a parallel translation of the impedance curve with falling impedances at higher u/d-ratios. The numerical solution and the analytical approach can be compared at cross-sections where u/d is small. Cross-sections 2 and 3 comply with this condition as can be seen in Fig. 5. The simulation at crosssections 2 exactly matches the analytic result; cross-section 3 shows little deviation due to the similar u/d-ratios.

#### D. Septum geometry

Because FEM takes the septum thickness into account, the numerical model is used for cell dimensioning. At a constant h/d-ratio, sufficient testing volume and constant septum thickness u the w/a-ratio is the remaining variable which has to be optimized along the cell.

Therefore, the three cross-sections shown in Fig. 4 represent the nodes along the GTEM cell length *l*. According to

Fig. 5 the *w/a*-ratio at cross-section 1 is 0,369 and 0,395 respectively 0,4 for the others to meet 50  $\Omega$ .



Fig. 5. Calculated wave impedance Z for cross-sections depending on the w/a ratio

Because the changes of the w/a-ratio along the cell direction are small, a linear fitting function is chosen which eases septum manufacturing. The fit given by equation (2) yields a tolerable error of the wave impedance.

$$\frac{w}{a}(l) = \frac{0,000028}{mm} \cdot l(mm) + 0.3662 \qquad l = [100mm..1312mm]$$
(2)

The maximum deviation is at the cell's end with 0,06  $\,\Omega$  or 2‰.

# E. Apex geometry

The inlet where the septum is connected to the coaxial cable, called apex, has to be treated separately because its h/d-ratio cannot be kept constant. The connector to the external attached coaxial cable demands an inner conductor at an h/d-ratio of 0.5. Hence, the first 100 mm of the septum adjust the ratio to 0.75 by keeping the 50  $\Omega$  condition. For easy manufacturing, the height adjustment is linear over the apex's length. Additionally, the septum thickness u has a significant influence due to the small absolute height d. The resulting apex shape needs to address all three issues. Therefore a forth order polynomial us used as fitting to meet 50  $\Omega$  conditions.

# F. Wave Impedance over GTEM cell

The overall resulting wave impedance along the cells geometry is shown in Fig. 6. From 0 to 100 mm the apex geometry is used to compensate the influence of the apex thickness and the adoption of the height ratio. The influence of the termination is not yet considered.

The small error in the septum's calculated wave impedance is considered negligible and will probably be exceeded by manufacturing tolerances.



Fig. 6. Impedance of GTEM cell along cell length

#### G. Termination

To avoid reflections at the cell's end the galvanic termination of the septum has to be 50  $\Omega$ . In this case an area resistance over the whole septum width is used. It consists of small surface mounted resistances connected in parallel on a printed circuit board. For this purpose, resistances with small line inductivity and stray conductivity are used. To provide the desired area resistance effect, the concentrated elements are positioned close to each other. Their distances must be smaller than  $\lambda/10$  of the minimum wave length at maximum frequency (1 mm for 3 GHz in oil) to avoid reflections.

Despite the galvanic termination, the energy of the electromagnetic waves demands consideration, too. Conventional oil stable EM absorbers and ferrite plates are suited for attenuating EM waves in the GHz range and are attached at the cell's termination wall, see Fig. 7.



Fig. 7. Oil-filled GTEM cell (interior view)

# H. Manufacturing of GTEM Cell

With the design shown in this contribution an oil-filled GTEM cell (Fig. 8) has been manufactured and can now be used for AF determination of UHF sensors for UHF PD measurement at power transformers.



Fig. 8. Oil-filled GTEM cell

## IV. CONCLUSION

Electrical and UHF measurement are influenced by the actual level of the PD source, the signal attenuation in the coupling path, the sensor sensitivity and the sensitivity of the measurement device. Because electric measurement equipment (coupling capacitors and quadrupole) can be calibrated it is suited for routine tests. To become a comparable method, UHF needs standardization of its measurement equipment: UHF antennas require calibration or at least a validation of their sensitivity. Therefore, the antenna factor needs to be determined under reproducible conditions which also meet inside-transformer conditions in the UHF frequency range (300 MHz – 3 GHz). To consider the radio frequency properties of the insulation inside transformers an oil-filled GTEM cell is designed to meet 50 Ohm conditions for measurement purposes. The cell provides a test volume with known electric and magnetic field strength and far-field

conditions using the TEM mode. The test volume must be chosen according existing typical antenna sizes and geometries. Using this setup, the antenna factor of any UHF sensor can be determined in oil to characterize the sensor. Hence, an evaluation of the sensor quality and its performance in comparison can be made. The test setup has to be compatible for various systems like drain valve mounted sensors and plate sensors which are integrated directly into transformer tank walls. A standard setup like the presented approach provides comparability and can therefore be valuable for the UHF measurement to become an accepted method for transformer diagnostics and monitoring.

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