Sept.20-25, 2015, China

CIGRE SC A2 COLLOQUIUM 2015

Practical Sensitivity of online UHF PD Monitoring on Large Power Transformers

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ABSTRACT

The reliability of electrical energy networks depends on the quality and reliability of its electrical equipment, e.g. power transformers. Local failures inside their insulation may lead to catastrophic breakdowns and may cause costly outages and penalties. To prevent these destroying events power transformers can be tested on partial discharge (PD) activity before commissioning and can be monitored on PD activity during service. This contribution compares the conventional electric method according to IEC 60270 [1] and the electromagnetic method concerning their suitability for transformer surveillance. Both methods are evaluated using a test setup using an artificial PD source with constant charge and changeable position. Especially the correlation between the apparent charge according to the IEC measurement in a calibrated setup and the actual charge of the source is taken into account.

The idea of a standard calibration procedure based on the characterization of ultra-high frequency (UHF) sensors by the antenna factor (AF) is introduced to ensure the reproducibility of the monitoring system´s sensitivity and the comparability of UHF measurements devices. 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 introduced for correct permittivity.

Concerning UHF PD measurements, the sensitivity of installed sensors and measurement devices are determined and evaluated. The evaluation is realized by the idea of transmitting electromagnetic waves through the transformer tank from one UHF sensor to another UHF sensor which is called sensitivity check procedure. The procedure requires high signal amplitudes in the UHF frequency range to enable signal transmission through the transformer due to damping in the propagation path. Therefore, a new high power UHF impulse generator is proposed and its properties like signal amplitude, rise time and phase synchronization are discussed.

KEYWORDS

Power Transformers, Diagnosis, Monitoring, Acceptance Test, Partial Discharge, Electromagnetic, UHF, Impulse Generator, Antenna Factor, Sensitivity

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1. 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. 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 [2]. 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 to IEC 60270 and directly by electromagnetic measurements in the ultra-high frequency range (UHF: 300 MHz – 3 GHz). Because DGA only provides an indicator about 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 IEC 60270 [1] which is required for acceptance certificates at routine testing. Therefore, the apparent charge Q_{IEC} has become an indicating factor for transformer quality. Acoustic PD measurement seems to be less suitable for PD monitoring at power transformers because of its bad signal to noise ratio. It can be used for localization of PD triggered by UHF or electrical signals.

UHF measurements use a second characteristic of PD, its ability to radiate electromagnetic waves. Originally, UHF measurements were developed for gas insulated switchgears (GIS) [3]. The method requires antennas inside the tank for transformer measurements. Therefore, the Cigré Working Group WG A2-27 recommends in brochure 343 to provide DN50 valves for the later fitting of UHF probes as valves provides the greatest flexibility for the future. Alternatively, dielectric windows can be provided for UHF sensors [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 busing (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].

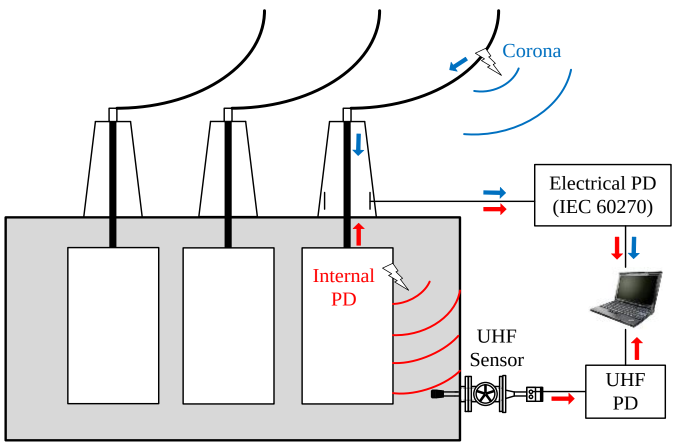


Figure 1: Signal propagation of UHF and conventional PD measurement at a power transformer with internal (red) and external PD (blue) [6]

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 on-line PD monitoring [9]. To become an accepted quality factor, UHF has to be proven as reliable, which can complement electrical measurements. Basically, it lacks a calibration which makes UHF sensors and measurement systems comparable to each other. For electrical PD measurement a calibration procedure for the ratio between capacitance of specimen and coupling capacitor is 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. COMPARISON OF CONVENTIONAL AND UHF PD MEASUREMENT

The fundamental difference between the two methods is their physical values. The apparent charge level of the electrical measurement is determined by integration of the recharging current. For UHF, the electromagnetic radiation of the PD is measured using antennas. 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 in a power transformer. A linear physical relationship 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 but is not given for complex structures like power transformers [10]. In theory, both measured variables contain the same information. A rough estimation can be derived from laboratory experiments: An UHF signal in the range of $U_{UHF,antenna} = 10\,mV$ corresponds to an apparent charge in the range of $Q_{IEC} = 100\,pC$. However, some PD sources do not radiate detectable UHF and can only be measured conventionally. Also, electrical signals from PD that are located deep in the winding, are strongly damped and lead to very small apparent charges at the measuring point which can be below noise level.

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 [11], [12] considering its inductance and stray capacities, see the equivalent circuit in Figure 2 a). In addition, the internal capacities at the fault location are unknown. This can be illustrated by a void inside the insulation system. Figure 2 b) shows a simplified equivalent circuit of a void and a intact surrounding insulation system.

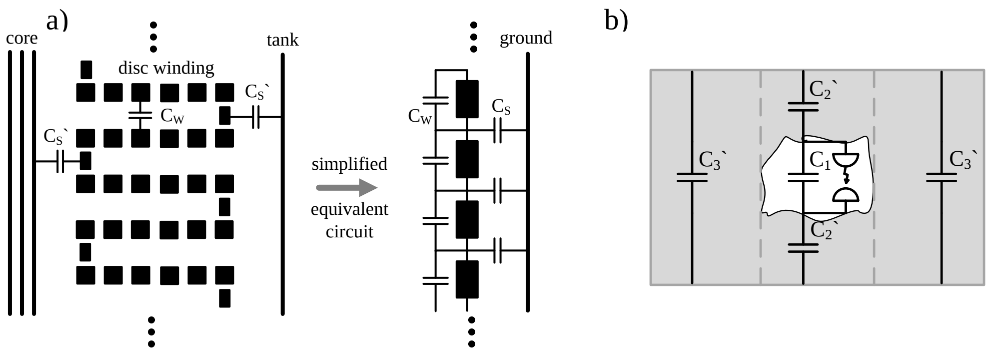


Figure 2: a) Transformer disc winding as low-pass filter for electrical PD signals
b) Internal capacitances of a void (C1), and of the surrounding insulation material (C2’ and C3’) [13]

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 used for electrical PD measurement according to IEC60270, either external or the capacity of the bushing (as shown in Figure 1). Only the recharging current of the connected coupling capacitor can be measured. Because 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 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 mainly through oil and pressboard, independent from the galvanic coupling path. Nevertheless, the electromagnetic wave is attenuated and can also be reflected at metallic parts. The entire attenuation of the electromagnetic propagation inside a transformer is relatively low; approximately 2 dB per meter for transformer oil [10]. Since PD location is not known inside the transformer, electromagnetic waves propagate through an unknown system before they reach the UHF sensor. As the damping along the propagation path is unknown, the actual PD level is also not known.

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

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. Considering damping, calibration must also be taken into account. 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 two questions:

- Which part of the propagation path can be included in the calibration and hence does not unknowingly influence the measured result?
- Which parts are not included into calibration and what factors do 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. By calibration the ratio of coupling capacitance C_K and the capacitance of the DUT C_T is determined and compensated. The measured value after calibration is known as apparent charge q_s. Therefore, actual and apparent charge of PD signals close to the calibration point (e.g. at the lead exit) are similar. PD signals which originate farther from the calibration point are influenced by the inside transformer propagation path which cannot be calibrated.

Since 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 measurement devices. In principle, the signal path which can be calibrated is very much the same as at 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. Therefore, the antenna factor has to be measured and then included into the calibration. This makes calibration more complex than for the electrical measurement and the application of a calibration signal is not sufficient. A detailed consideration of UHF sensor calibration is provided in chapter 3.

Side note: The calibration of UHF measurement does not establish a physical relationship between the UHF antenna voltage (in mV) and the apparent charge (in pC) of the electrical measurement. Several publications state this connection as non-existent for complex structures like power transformers [10].

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, artificial 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 the 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 artificial PD source consists of two copper plates connected through a capacitor and a gas-filled discharge tube (GDT). It is galvanically connected to ground on one side and couples to the HV winding through the stray capacity of one of its copper plates [13]. It provides a reproducible, phase stable, constant charge conversion. The constant charge is set to 1000 pC and it emits electromagnetic radiation and hence can be used as UHF PD source, additionally.

During the experiment, the position of the source's location is changed and the distance between top of the tank and source is slowly increased stepwise. 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 output of each sensor at changing source location is shown in Figure 3 b). Because damping increased by approximately 2 dB/m in a uniform propagation path, signal weakens for sensors 1 and 2 if the distance to the source increases (note that sensor 1 is at the bottom of the tank). 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. An attempt to explain this that not the PD source itself radiates the electromagnetic wave, but the surrounding structure, e.g. the winding, is the active antenna. Hence, propagation changes at each position by the influence of the changing emitting antenna formed by the winding and the surrounding structure.

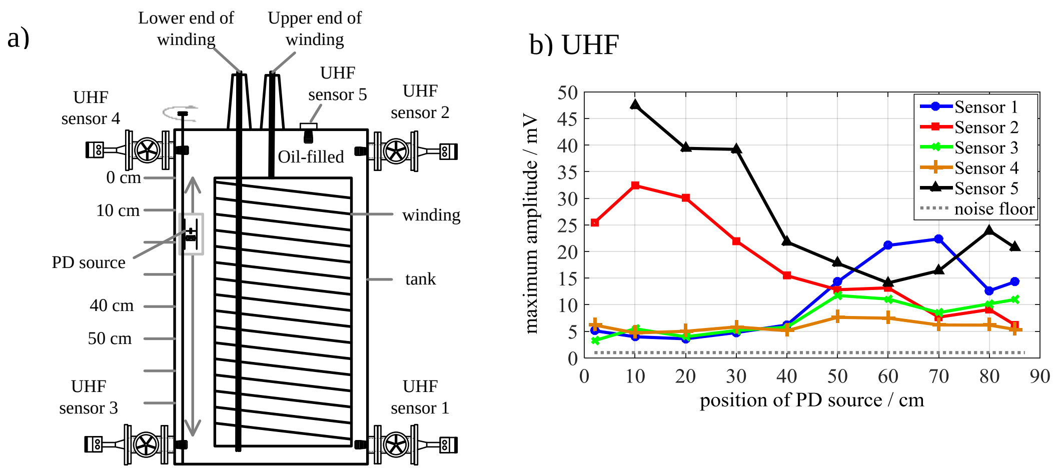


Figure 3: a) Test setup for both electrical PD measurement according to IEC and UHF measurement b) maximum measured UHF levels of UHF sensors 1-5 [13]

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

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

PD are measured using a calibrated system either on the upper or the lower ending of the winding. The results are shown in Figure 4 a) (broadband) and Figure 4 b) (narrowband). The black line shows the actual 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. Also, 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 (Figure 4 b) show a comparable behavior of upper and lower winding measurements. 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 at 1 MHz shows a more expected behavior. Nevertheless, both results lead 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 charge, but regarding broadband measurements also overestimation is possible.

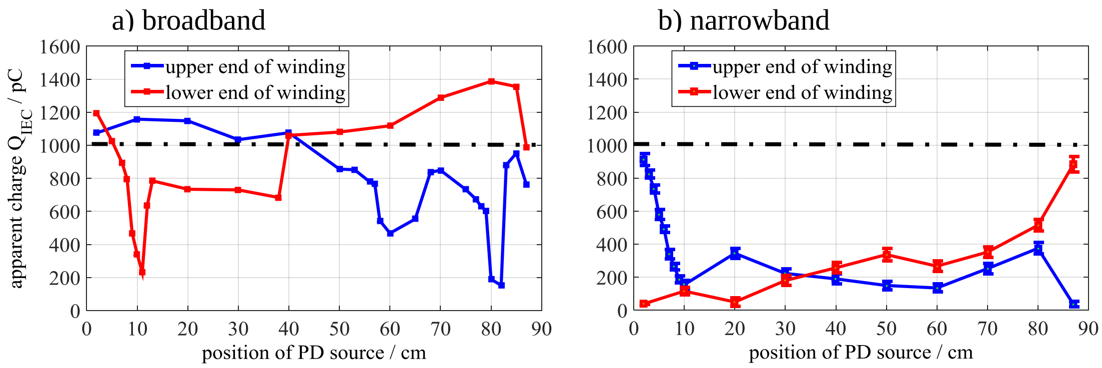


Figure 4: Apparent charge of electrical PD measurement at upper and lower end of winding.
a) IEC broadband measurement
b) IEC narrowband measurement
Dotted line: Actual charge of the source [13]

3. COMPARABILITY OF UHF MEASUREMENT

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

1. Type and actual level of the PD source
2. Signal attenuation in the coupling path, see chapter 2
3. Sensor sensitivity (the UHF antenna or the coupling capacitor and the quadrupole)
4. 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 sensor's influence can be achieved for the UHF method, 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 Transverse Electro-Magnetic cell (TEM cell) in a frequency range up to 950 MHz [14]. 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. Therefore, proper AF determination requires an oil filled measurement setup capable of full UHF frequency range. To meet these conditions, an oil-filled Gigahertz Transverse Electro-Magnetic cell (GTEM cell) is required [15].

3.1. UHF Sensor Characterization

The antenna sensitivity depends on its design with respect 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 factor AF is used which is defined as

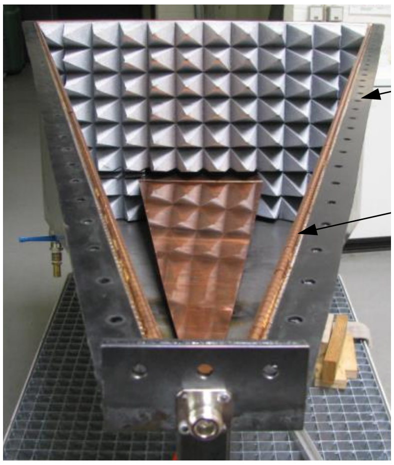
$$AF(f) = \frac{E(f)}{U(f)} \qquad (1)$$

where $U(f)$ is the voltage at the antenna terminals and

$E(f)$ is the electric field strength at the antenna.

Another factor suitable for characterization is the antenna gain which is often specified by the effective length l_{eff}, where l_{eff} is defined by the inverse antenna factor. For the evaluation of the antenna sensitivity an oil-filled GTEM cell is used, shown in Figure 5 a) and b).

a)



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. Also, the electric field strength E_{hom} in the test volume has to be known for AF calculation of the EUT.

3.2. GTEM Cell Design

To ensure before mentioned field characteristics reflections at both, the input and the termination of the cell have to be avoided. Therefore, the entire cell has to operate in 50 Ω domain if it is filled with mineral oil, meaning its wave impedance Z has to be adjusted to meet 50 Ω, too. The ratio between cell width and septum width is adjusted by using finite element method (FEM) simulations to meet 50 Ω along the entire cell [6]. To avoid reflections at the cell's galvanic terminations of the septum has to be 50 Ω. At its end an area resistance over the whole septum width is used. It consists of small surface mounted (SMD) resistors connected in parallel on a printed circuit board (PCB). SMD resistors with small line inductivity and stray conductivity are used. Despite the galvanic termination the energy in the electromagnetic field demands consideration, too. Therefore, EM absorbers and ferrite plates attached at the cell's termination wall are suited for the attenuation of EM waves in the GHz range, see Figure 5 a) [15]. The GTEM cell is evaluated by three parameters. The electrical field strength inside the test volume, the wave impedance with time domain reflectometry (TDR) and the standing wave ratio (SWR) at the input port of the cell. For evaluation of the test volume, electrical field strength measurement can be compared to the design values, simulated with FEM simulation. The 50 Ω design of the septum can be evaluated with TDR, which shows a constant wave impedance of 49.2 Ω along the cell length.

3.3. Antenna Factor Measurement with GTEM Cell

The AF of a UHF sensor can be determined using a transmission factor (S21) 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).

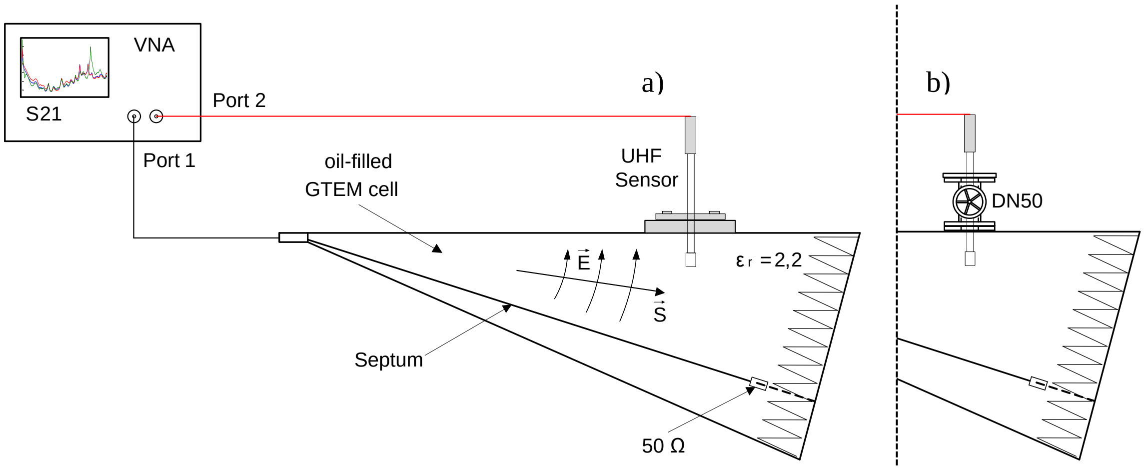


Figure 6: Transmission measurement (S21) for AF determination
a) UHF sensor direct mounted to the cell without oil valve
b) UHF sensor installed via DN50 oil valve to the cell

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 S21 can be converted into the AF of the UHF sensor if the electric field strength in the test volume is taken into account. Two different AF of a UHF drain valve sensor shown in Figure 7 are presented in Figure 8.

Figure 7: UHF sensor for standard drain valve DN80

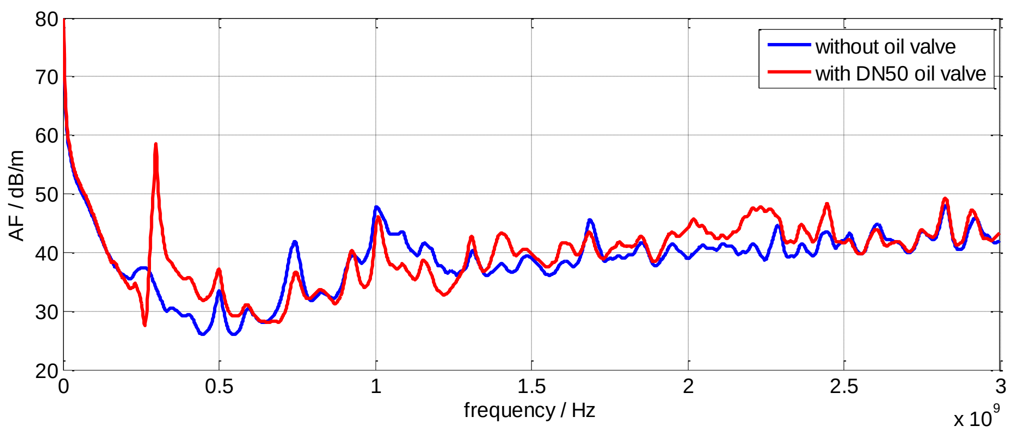


Figure 8: Antenna factor (AF) of UHF sensor measured in GTEM cell
Blue curve: UHF sensor direct mounted to the cell (shown in Figure 6 a))
Red curve: UHF sensor installed via standard DN50 drain valve to the cell (shown in Figure 6 b))

The UHF sensor has the highest sensitivity in the frequency range of 300 MHz up to 1 GHz. The measurement of the 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 red curve in Figure 8 shows. The highest influence of the valve occurs at approx. 300 MHz (see resonance). Compared to a real transformer the GTEM cell calibration measurement only considers the influence of the sensor. Surrounding structures which might occur inside transformers do also influence the antenna's geometry and hence it's AF, but are not calibrated in this standard test setup.

4. SENSITIVITY CHECK WITH UHF IMPULSE GENERATOR

4.1. Proof of Sensitivity

The electrical PD measurement calibration uses a pulse which is fed into the bushings or the coupling capacitor, not directly into the winding. Thus, the propagation path in the transformer is not taken into account. The electromagnetic measurements can use an UHF pulse which is fed to one sensor and measured by a second if two or more sensors can be applied to the transformer. If the sensors are on opposing sides of the transformer as shown in Figure 9, the sensitivity check includes the signal path through the transformer [16], [17]. Hence, it is not possible to show the sensitivity for PD originated in the winding for both, the UHF method and the conventional measurement.

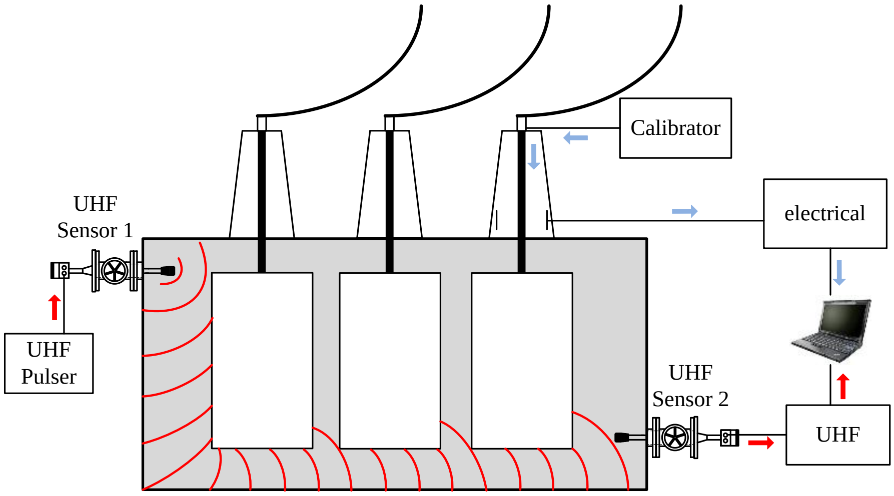


Figure 9: Blue: calibration of electrical measurement, no sensitivity check through the propagation path
Red: sensitivity check of electromagnetical PD measurement trough the propagation path

4.2. Experience with Impulse Generators at Power Transformers

A UHF sensitivity check should be done when an UHF monitoring system is installed. This procedure is normally done with an UHF pulse generator, designed for UHF sensitivity checks in GIS systems with an approx. maximum amplitude $\hat{U}_{pulse}$ =50..60 V (in 50 Ω domain) [3]. For small transformers this is sufficient. Larger power transformers with higher distance between the UHF sensors often provide higher signal attenuation and signals strength at the second (measuring) sensor is below noise level, see Figure 10. Hence, the UHF sensitivity check fails.

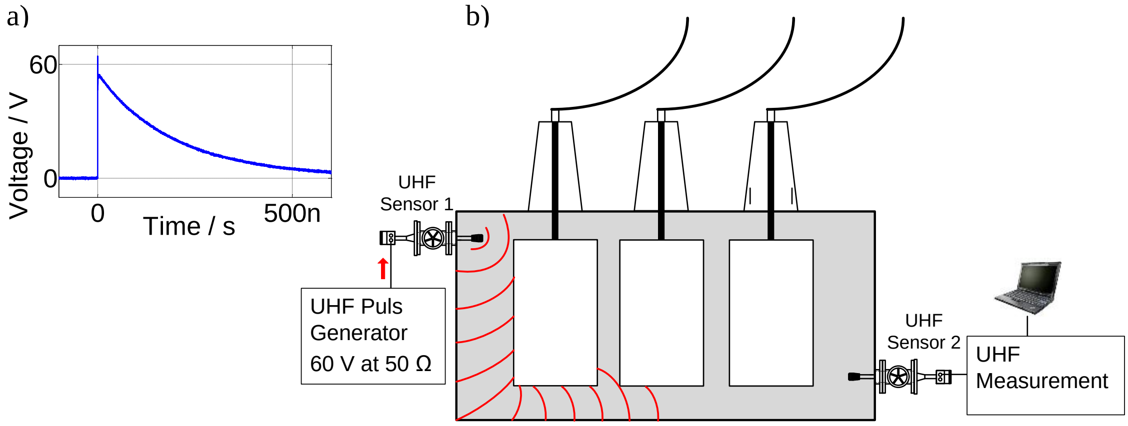


Figure 10: a) 60 V impulse of UHF impulse generator
b) Failed sensitivity check at large power transformer

Due to the lack of state of the art UHF impulse generators with higher amplitudes $\hat{U}_{\mathrm{pulse}}$ a high power pulse generator normally used for EMI/RFI/EMC-applications is tested at a large power transformer, see Figure 11. Its amplitude is approx. $\hat{U}_{\mathrm{pulse}}$= 250 V (in 50 Ω domain), see Figure 11 a). The resulting impulse power is about 1,25 kW. Nevertheless, a sensitivity check failed at the same large power transformer from the previous test.

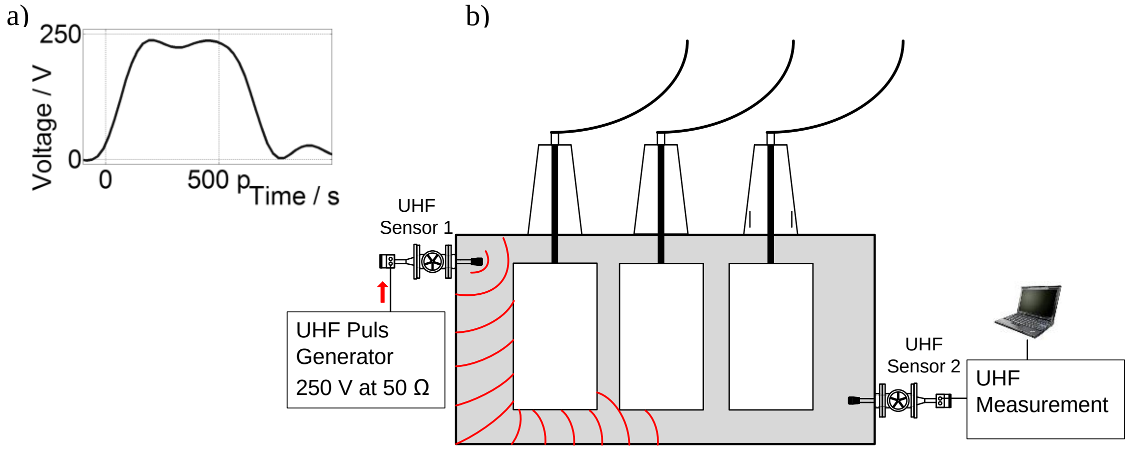


Figure 11: a) 250 V impulse of EMI cable impulse generator
b) Failed sensitivity check at large power transformer

4.3. Investigation on Transmission Characteristic of Power Transformers

The impossibility to perform a sensitivity check arises the question of the frequency response of the propagation path. Therefore, two UHF sensors are installed at a power transformer and the transmission factor S21 is measured using a VNA in the frequency range from 300 kHz to 3 GHz. In Figure 12 and Figure 13 the measurement setup and the measurement results are presented.

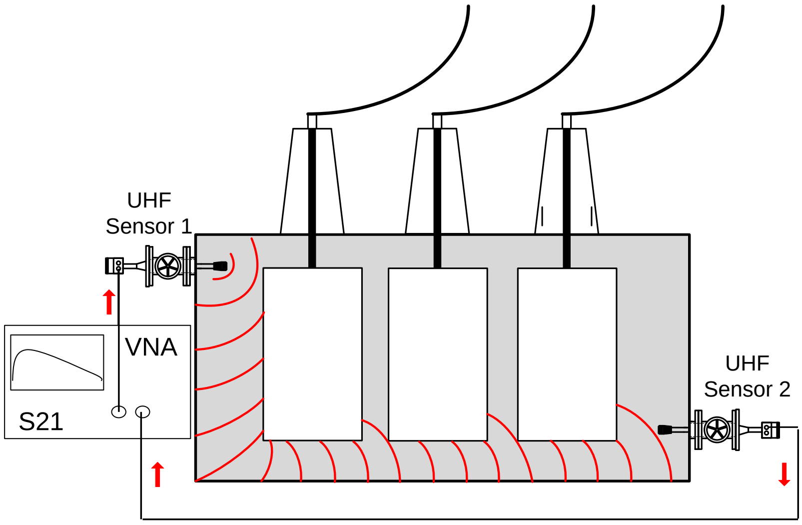


Figure 12: Transmission measurement from UHF sensor to UHF sensor through a power transformer

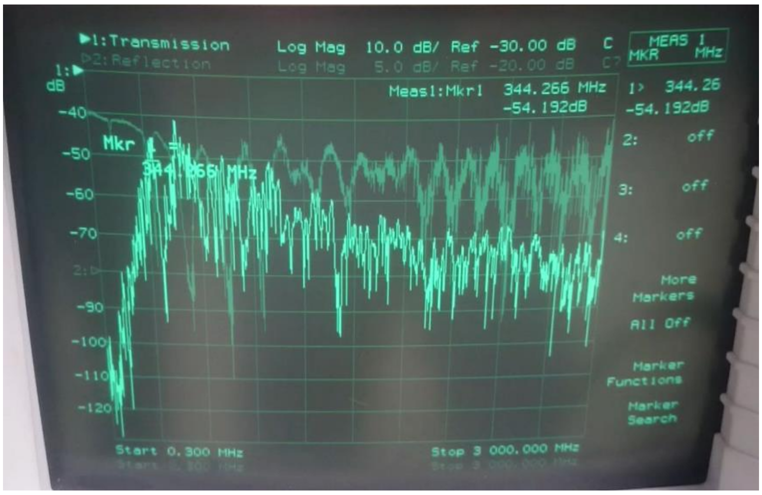


Figure 13: Transmission factor S21 measurement through a power transformer

The transmission measurement has same shape comparable to the AF of the used UHF sensors. The transmission with lowest damping occurs at a frequency range from approx. 300 MHz 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 8).

4.4. Recommendation for UHF Impulse Generator for Sensitivity Measurement at Power Transformers

The impulses shown in time domain in Figure 10 a) and Figure 11 a) are transferred in frequency domain in Figure 14.

The 250 V EMC pulse generator provides between 20 dB and 30 dB higher amplitude than the 60 V UHF pulse generator (in the frequency range from 300 MHz - 600 MHz). Therefore, the EMC impulse seems to be more suitable for this application. In order to enable UHF sensitivity checks a new very high power UHF impulse generator is in development which provides high impulse amplitude in 50 Ω domain and flat spectrum up to several 100 MHz. The high bandwidth requires rise times $\tau_{rise} \leq 100$ ps.

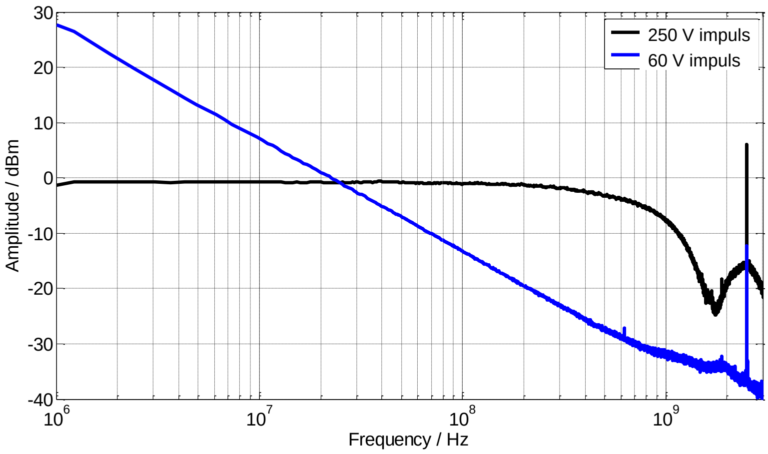


Figure 14: Frequency spectrum of pulse generators shown in Figure 10 and Figure 11

5. CONCLUSION

The comparison of electrical and UHF PD measurement methods shows that the detailed propagation path and its damping effects 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 capacitor and the quadrupole). The signal propagation inside the transformer remains unknown. As experiments show, the unknown path does have a significant influence on the measured 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.

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 of the UHF method. This step is essential for comparable UHF measurement independent of the used sensors. 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.

A sensitivity check cannot always be performed at large power transformers, as onsite measurements using state of the art UHF impulse generators show. 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. Transmission factor measurements at power transformers will have to be proof this thesis.

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