Partial Discharge Measurement in the Ultra High Frequency (UHF) Range

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ABSTRACT

The paper provides essentially a summary of PD measurements applying the UHF range in order to increase the detection threshold, to improve the localization accuracy and to perform on-line measurements of Partial Discharge (PD) in noisy environments. The electromagnetic UHF technique offers good signal to noise ratios, because external PD signals and disturbances can be shielded effectively. A new developed method allows the localization of PD in gas-insulated substations (GIS) by frequency domain measurements. The basic idea is the displacement law of Fourier transformation. The interference phenomena of superposed signals from two sensors give information about the time delay of the sensor signals. On-site PD measurements are made at cable connectors by means of monopole antennas housed in a barrel sleave, while the cable is in service. Thus a sensitive PD measurement even in noisy environment is possible. PD-measurements on several 72 kV cable connectors were performed in an unshielded laboratory. On-site measurements during operation showed the great potential for condition assessment. For decoupling sensitive UHF PD signals from the inner of a power transformer tank UHF sensors applied through drain/oil valves are used. Experimental studies indicate that all relevant types of PD possibly occurring within a transformer emit high frequency spectra to be detected with UHF sensors. Furthermore in laboratory experiments and on-site measurements very moderate UHF signal attenuations have been observed.

Index Terms — **Gas insulated switchgear, cable accessories, power transformers, on-site partial discharge measurement, UHF-sensor, condition assessment.**

1 INTRODUCTION

PARTIAL discharges (PD) can constitute a high risk for the dielectric stability of an insulation system. Therefore PD measurement is of a tremendous importance to assess the condition of high voltage equipment. Different PD measuring techniques are using different physical peculiarities of the PD phenomenon e.g. electric currents (according to IEC 60270), gas formation (dissolved gas analysis), electromagnetic (UHF-range) or acoustic radiation. Well-known and approved partial discharge (PD) measurements according to IEC60270 and measurement of µV according to IEEE .57.12.90-1999 are the basis for e.g. acceptance tests of the insulation system of high voltage equipment. As a powerful diagnostic tool there is an increasing demand to evaluate also installed equipment in service by means of PD measurements. Unfortunately conventional methods show some drawbacks and limitations if performed on-site/on-line e.g. regarding the applicability of sensors and being receptive for several disturbances. For offline measurements there are possibilities to reduce external noise e.g. use of spectrum analyzer and external voltage source with variable frequency.

In general three information are important regarding a PD activity – its level, its type and its location. The information of the PD origin together with the knowledge of the surrounding insulation material is essential to assess e.g. the risk potential of the fault, because there are PD-resistant materials for example or different types of PD-sources which may disappear during the test. It is of great importance to know about the PD origin to plan and start maintenance / repair actions cost and time efficiently.

Manuscript received on 10 April 2008, in final form 18 August 2008.

The advantages of the unconventional PD measuring methods are their (i) wide immunity against external disturbing signals on-site, (ii) the fact that the sensors need no electrical connection to the high voltage circuit and (iii) the inherent possibility of determining the failure location (localization of the PD) using arrival times of these signals. Corona as strongly interfering electrical process on-site, has only a reduced influence on UHF measurements (contrary to electric PD measurement according to IEC 60270). The electromagnetic (UHF) technique offers very low noise levels in GIS and transformers since the housings act as Faraday cage shielding external noises successfully. An often mentioned drawback of these methods is that no assured apparent charge information (electric level in pC) is delivered. This issue is increasingly addressed with so-called Performance and Sensitivity Checks [1 - 3]. But it has to be considered that exact measurement of apparent charge is not really needed for measurement on complex insulating system, for the investigation of the risk the behavior of the PD-source during the test is much more important.

The different application aspects of the UHF PD measuring methods and their interpretation will be presented in this contribution for GIS, cable accessories and power transformers.

2 GAS-INSULATED SWITCHGEAR

Beside acoustic impulses, which also can be used for localization, very fast electric pulses with rise times below 1 ns, are emitted by a PD source and propagate in all directions along the GIS duct. A simple and obvious way of locating PD in GIS is the measurement with the time-of-flight method. By the time-of-flight technique the time difference between the wave fronts arriving at two UHF-PD-sensors indicates the location of the PD source. The time difference (Δt) is usually in tens of 1 ns, so that a fast digital acquisition has to be applied for measurements.

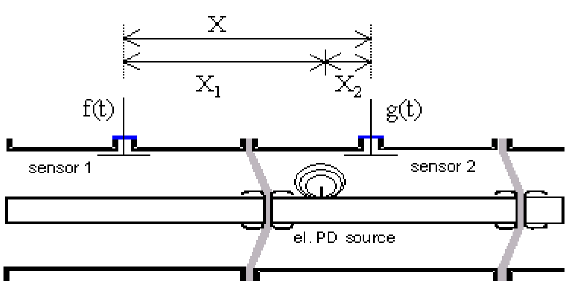

Figure 1. Cross section of a GIS with PD-sensors.

The distance X_1 can be calculated with the equation (1) in case the time difference (Δt) is known.

$$X_1 = \frac{X-(X_2-X_1)}{2} = \frac{X-c_0\cdot\Delta t}{2} \quad (1)$$

2.1 THEORETICAL BACKGROUND

Another method to determine the time difference (Δt) and to localize PD in GIS is to use the frequency domain. A measurement procedure with a spectrum analyzer instead of an expensive fast digital oscilloscope is more economical. The interference phenomena of two sensor signals, which are added, give information about the time delay (Δt) between the signals. The idea is based on the displacement law of a Fourier-transformation (equation 2) of the received signals.

$$FFT\left[f(t-\Delta t)\right] = FFT\left[f(t)\right]\cdot e^{-j\omega\Delta t} \quad (2)$$

To visualize the interference phenomena, three power spectra are needed. The power spectrum is the absolute value of the complex Fast Fourier Transformation (FFT). The three measured power spectra are obtained from Sensor 1 (equation 4), Sensor 2 (equation 5) and the added signal of Sensor 1 and 2 (equation 6) with a conventional spectrum analyzer. The last signal is obtained by means of a Radio Frequency power combiner. These three signals are combined in equation 3 in order to get the theoretical cosine function. The time difference (Δt) can be calculated with the resulting cosine function in case the approximation f(t) ~ g(t) is possible. This cosine function has equidistant minima (Figure 2). The distance between these minima represents the interference frequency Δf = 1/Δt , which can be interpreted as interference phenomena [3].

$$\frac{H(\omega)}{F(\omega)+G(\omega)} = K(\omega) \approx K_t(\omega) = \left|\ \cos\left(\frac{\omega\cdot\Delta t}{2}\right)\right| \quad (3)$$

$$F(\omega) = \left|FFT\left[f(t)\right]\right| \quad (4)$$

$$G(\omega) = \left|FFT\left[g(t)\right]\right| \quad (5)$$

$$H(\omega) = \left|FFT\left[g(t)+f(t-\Delta t)\right]\right| \quad (6)$$

Two similar signals f(t) and g(t) are required to obtain useful results from equation (3). To keep the characteristics of both signals similar, the effect of dispersion should be kept as small as possible [4]. The group velocity (v_g) of the Transversal Electric- / Transversal Magnetic-wave modes is frequency dependent, which is a precondition for dispersion. Below the lowest critical frequency of all modes (in GIS the f_c of TE_{11}), only TEM-modes are able to propagate [5]. A requirement for a successful result ($K_t \approx K$) is a sensitive measurement in this frequency range.

2.2 Interpretation of Frequency Domain Measurements

With different GIS types and set-ups the interference phenomena are not always clearly visible and the distance between the minimum (interference frequency) Δf is not manually estimable. An objective method is necessary in order to fit the combined measurement K(ω) with theoretical cosine functions $K_t(\omega)$ of different Δt. The best correlation in a manually selected frequency range of the measured combined signal with the theoretical cosine function is determined by the calculation of the maximum cross-correlation. The theoretical function with Δf = 1 / Δt possesses the largest correlation and thus the value of the cross-correlation is maximal [4]. A disadvantage is, that the interesting frequency range of the Cross-Correlation Method (X-Corr. Method) and the Minimum Method must be determined manually (Figure 2).

To determine the distance Δf of the minima even with more complex measurement set-ups, an analysis with wavelet transformation can be applied. The wavelet family is chosen very similar to the theoretical cosine function $K_t(\omega)$. Thus a large selectivity to the searched interference is possible in relation to resonances and disturbances in complex test set-ups. The result of this Wavelet Method shows the similarity of the measured spectrum K(ω) over the complete frequency range ω and theoretical cosine $K_t(\omega)$ with a certain interference frequency Δf. The differentiation between an interference, which belongs to a corresponding delay time, and another, which belongs to disturbances or reflections, takes place over maximum values and plausibility (Fig 4). A good result is visible by increased signal energy over a concrete interference frequency Δf and over a wide frequency range. The absolute value of the time delay |Δt| can be estimated by the interference frequency Δf.

2.3 EXAMPLE

Figure 2 shows the measurement of the interference phenomena in a bay of a 300 kV GIS. The two sensors are capacitive UHF-PD-sensors, placed at the bus bar and at the termination of the GIS (circuit breaker: open). This distance corresponds to the typical distance of sensors. The PD-source was a pulse generator with an antenna.

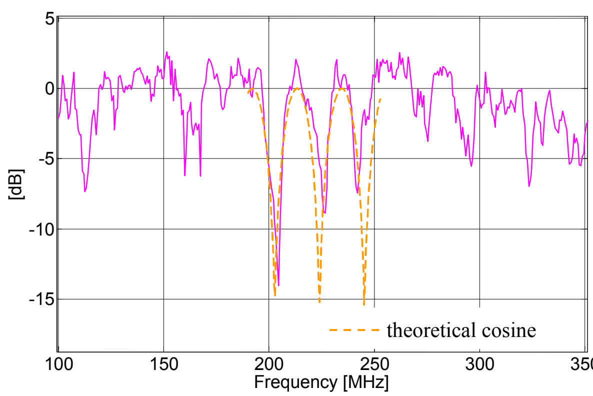

Figure 2. Calculated combination of the power spectra for the measurement at the 300 kV GIS.

The time difference is measured as Δt = 45 ns by using the oscilloscope. The theoretical cosine function matches best at Δf = 21.2 MHz with the X-Corr Method in a manually chosen frequency range (Figure 2). The Δt is calculated as 47 ns.

In this example the Wavelet Method evaluates a good result. The maximum value is at Δf = 22.5 MHz. The time difference Δt can be calculated as Δt = 45.4 ns (Figure 3 and 4).

Because of the more complex arrangement the evaluation of the measurement at 300 kV GIS bay (Figure 2) is not as simple as the measurement at a bus bar or a GIL. The reasons are the additional reflections in the GIS. More complex methods like the Wavelet Method are able to interpret these signals.

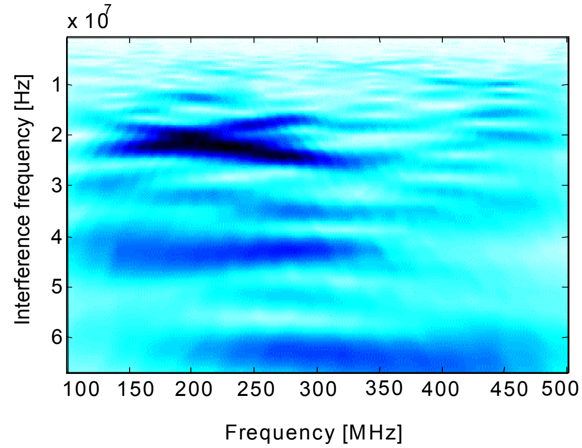

Figure 3. Wavelet Method applied to measurement at 300 kV GIS bay.

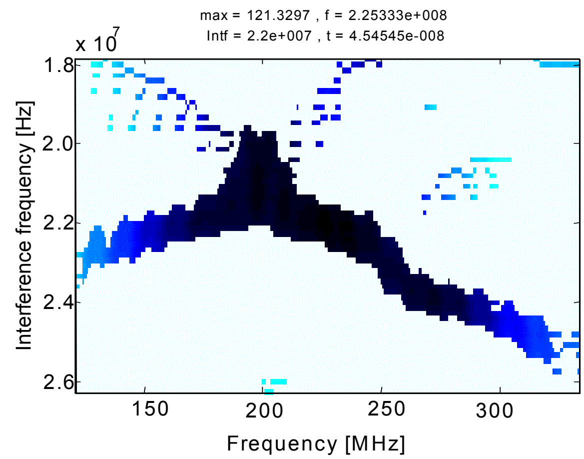

Figure 4. Detailed view of the Wavelet Method (Fig 3) with maximum evaluation.

3 CABLE ACCESSORIES

3.1 PRINCIPLE OF DIAGNOSIS AND LAB TESTS

Utility experience shows that poor termination and jointing is the major cause of cable failures [6]. This is due to the fact that, in contrast to the cable itself, these components are assembled and installed under on-site conditions and thus exposed to the higher risk of defects and contaminations [7].

Modern plug-in cable connectors (terminations) for GIS and transformers are made from silicone rubber. The electrical life span of this high polymeric material normally exceeds 40 years, but only in absence of PD activity that inevitably causes material's degradation. Although there are several well known off-line test techniques (i.e. dc, damped oscillating wave, very low frequency voltage tests), which are successfully applied to diagnose power cables including their accessories, they all need a line disconnection, load flow redispatching and a separate voltage source to energize the cable line apart from the network [8]. The online UHF test approach overcomes these difficulties allowing sensitive measurement on the terminations, while the cable is in normal operation [9].

Figure 5 demonstrates the principle of UHF diagnosis on the plug-in cable connectors. A portable metallic housing is clamped on the cable behind the connector and fulfils two functions: firstly, as a housing for field couplers (antennas) and secondly, as a grounded screen against the disturbances from outside.

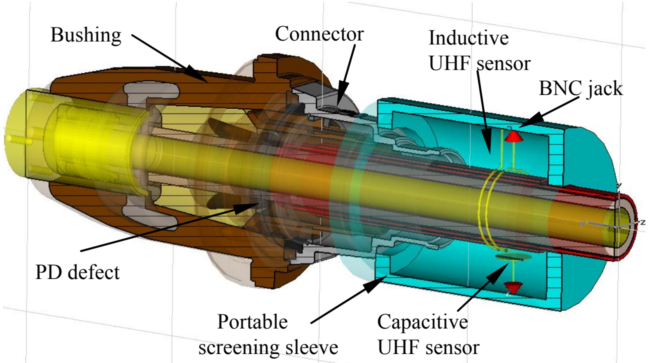

Figure 5. Plug-in cable termination and principle of the UHF PD diagnostics.

The transient electromagnetic field caused by PD can be detected by coupling its electric (capacitive sensor) or magnetic (inductive sensor) components. The capacitive sensor represents a copper disc with the diameter of 2 cm, soldered to the copper pin in the middle. The inductive sensor is a two-winding coil made from an insulated wire. One end of the coil is grounded; another one is connected to a measuring coaxial cable RG-214.

Nanosecond pulses emitted at the PD fault location and captured with different sensors are pre-amplified, filtered and processed with a computer-based oscilloscope. As diagnosis parameters the pulse's shape, its spectral characteristics and repetition rate are considered. Phase resolved PD patterns were taken to figure out if the pulse activity is power cycle related [10].

The calibration of the UHF method in terms of amount of charge is not possible. In order to perform a sensitivity check comparative PD measurements were performed with built-in artificial defect using both the UHF method and the conventional method according to IEC 60270. An apparent charge below 5 pC turned out to be detectable by both type of UHF sensors. Lab tests also demonstrated that one could easily discriminate the internal PD defects in the termination insulations from corona noise originated in neighboring equipment insulated with air or SF_6 [10].

3.2 ON-SITE EXPERIENCE

On-site PD measurements are made on cable terminations in the manhole of a GIS, while the cable is in operation as shown in Figure 6.

Figure 7 shows such a typical fast pulse picked up on a connector on-site. The frequency spectrum of this pulse is plotted in ffigure 8. Besides some broadcast (DVB-T) and GSM frequency spikes, there are several other high frequency components that indicate presence of PD activity. The frequencies around 700 MHz and 1.5 GHz were detected with this specific connector only, thereby indicating a critical condition. 10 days after the measurement the connector failed and thus the indication was proved.

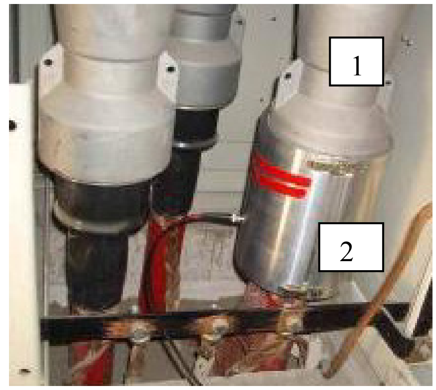

Figure 6. On-site test set-up: portable screening sleeve with the UHF sensors (2) mounted on each termination (1) in turn.

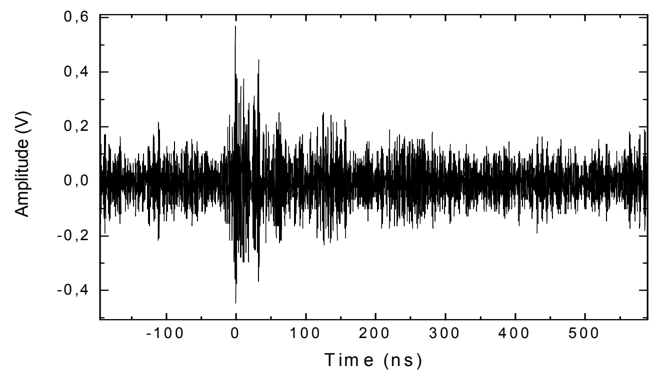

Figure 7. Typical fast pulse emitted by the faulty termination on-site.

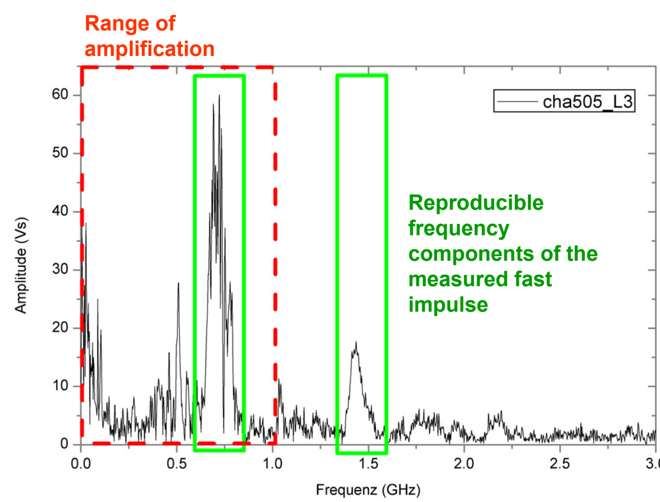

Figure 8. Frequency spectrum of PD-pulse at cable connector.

4 POWER TRANSFORMERS

For decoupling UHF PD signals from the inner of the transformer tank UHF sensors (acting mainly capacitive) can be installed through a drain/oil valve. Different sensor designs - monopole-formed, disc-shaped and cone-shaped – can be distinguished. While for laboratory test both types have been used, only the disc-shaped and cone-shaped sensors were applied in on-line measurements (Figure 9). The non-destructive application of the UHF sensors can be managed while the transformer stays in full service, since there is no galvanic connection needed to the high voltage circuit. Very low noise levels (due to shielding effects of the transformer tank) and low signal attenuation in solid insulation materials, oil and complete structures within transformers enable sensitive measurements even under noisy on-site condition.

Furthermore aspects as (i) verification of hydrogen and electrical PD measurements, (ii) alternative robust and easy PD decoupling, (iii) distinguishing between internal and external PD signals and finally (iv) locating of PD with additional acoustic measurements (as e.g. reported on a 200 MVA, 380/220 kV-single-phase Transformer [11]) underline the practical meaning of UHF measurements on transformers.

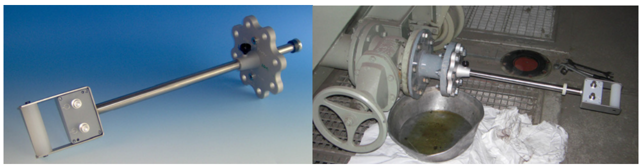

Figure 9. Active UHF drain/oil valve sensors for oil-insulated transformers (right: during installation).

4.1 SPECTRA OF UHF PD PULSES

The first question to answer when measuring PD in the UHF band on a power transformer might be whether PD of all types are sufficiently fast to radiate UHF pulses in oil. In the following a brief discussion of UHF spectra of different PD sources are presented.

All experimental measurements were conducted in such a way, that an occurring UHF PD signal triggered a simultaneous electric PD measurement, to get the apparent charge value according to IEC 60270. The relation to the standard PD-measurement method was hence obtained for every UHF PD signal. To capture the un-amplified UHF signals, a transient recorder with analogue bandwidth of 3 GHz was used. The experimental set-up for the investigation of "internal" PD sources consisted basically of a metal test tank with dimensions (1.0 x 0.5 x 0.5) m^3 without metal cover, the respective PD source and one disc-shaped UHF sensor [12]. The complete set-up was located in a shielded laboratory. The open tank should offer a quick decay of the UHF PD signals without strong resonances and hence limit the impact of the metal housing on the appearance of the electromagnetic signal.

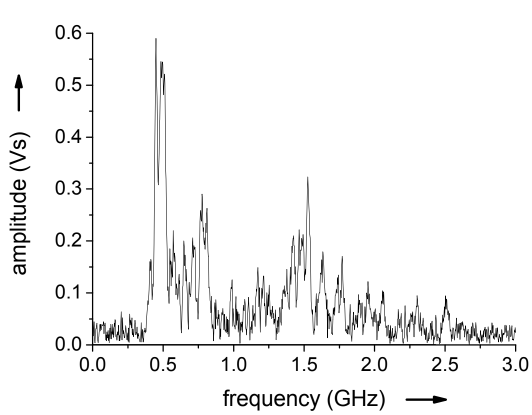

Figure 10. UHF PD spectrum of a needle-sphere PD-source in oil up to 3 GHz (apparent charge of 11.6 pC).

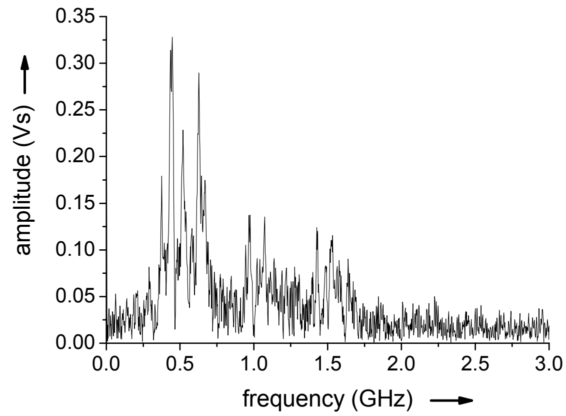

Figure 11. UHF PD spectrum of a surface discharge PD-source in oil up to 3 GHz (apparent charge of 356 pC).

As internal PD sources a needle-sphere source and a surface discharge source were used. The source for surface discharges consisted of an electrode sharpened on one side, a ground plate and a pressboard between them.

Figure 10 shows an UHF PD spectrum of a needle-sphere source (apparent charge 11.6 pC). Significant frequency components started around 385 MHz and went up to 2 GHz. The rise time of the UHF pulses was typically about 0.5 ns for that source.

The UHF PD pulses generated by the surface discharge source featured as well pulse rise times down to about 0.3 ns but sometimes also slightly slower pulses (rise times up to 2-3 ns). The UHF pulses remained detectable at all times. In Figure 11 an UHF PD spectrum of a surface discharge (apparent charge of 356 pC) with frequency components up to around 1.6 GHz is shown.

To generate external corona, the needle-sphere source was put outside of the tank in free air and the sensor on a position with 1.1 m distance and an inclination of 45° with respect to the source. Figure 12 gives the resulting UHF PD spectrum of the needle-sphere source in air with a quite high apparent charge of 2580 pC. The relevant frequency components decayed rapidly above 250 MHz. Thus distinction between external and internal PD is possible by the analysing the frequency content of the PD signal.

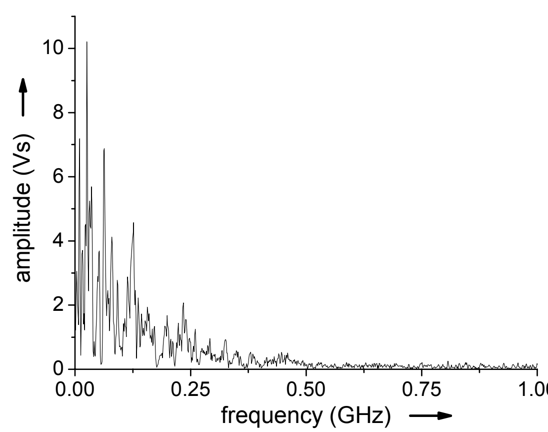

Figure 12. UHF PD spectrum of the same needle-sphere PD-source in air up to 1 GHz (apparent charge of 2580 pC).

PD measurements of voids and particles on floating potential are well reported. A pressboard void arrangement showed peak frequencies between 500-800 MHz in [13] while floating particle discharge had spectra up to 600 MHz [14] or up to 1 GHz [13] respectively.

The characteristics of the stated UHF spectra of different PD types are in general in good agreement with reported studies on similar PD defects [13-18]. This is indicating that all relevant types of PD, possibly occurring within a transformer, emit sufficiently high frequency spectra to be detected with UHF sensors.

4.2 CAVITY RESONANCE INVESTIGATION

The measurable UHF spectrum of a PD in a transformer depends, beside the natural radiation from the PD, strongly on different transfer functions included in the propagation path from source to measuring system. In addition to the sensor and cable characteristics, the surrounding materials and objects with their properties of transmission, scattering and reflection have a strong impact on the appearance of the recorded UHF PD signal. The transformer tank, as an almost closed metal enclosure, is highly reflective for incoming electromagnetic waves. To emphasize that scattered nature of internal UHF signals inside of metal enclosures, a consideration of possibly present cavity resonances was made in a laboratory investigation.

The experimental measurements were again arranged in a small test tank with the dimensions of 1.0 m x 0.5 m x 0.5 m. A monopole antenna was used for decoupling the UHF PD pulses of a rod-plane PD source [12]. PD of apparent charges down to 50 pC was measured with a transient recorder (analogue bandwidth 1 GHz) without any amplification.

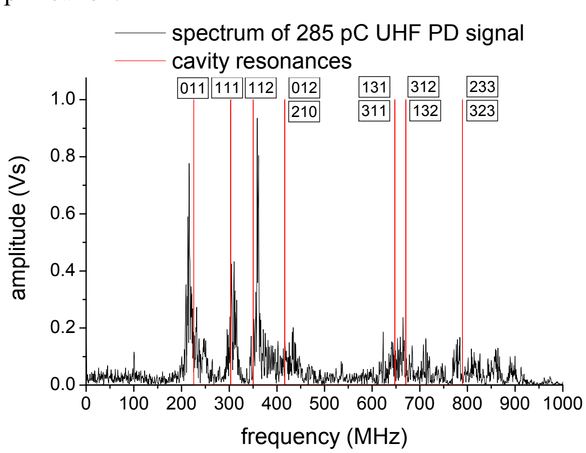

Figure 13. UHF PD spectrum of a rod-plane PD source (apparent charge 285 pC) with some dominant cavity resonances.

Regarding the tank as cavity bounded by conducting walls the following equation

$$f_{nmp} = \frac{c_0}{2\sqrt{\varepsilon_r}}\sqrt{\left(\frac{m}{a}\right)^2 + \left(\frac{n}{b}\right)^2 + \left(\frac{p}{c}\right)^2} \qquad (7)$$

defines the frequencies of cavity resonances, which can be calculated analytically. The symbol c_0 stands for the speed of light, ε_r can be filled with 2.2 for oil and *a, b, c* are the geometric dimensions of the tank. For a proper computation of the cavity resonances *m, n, p* should be filled with whole numbers and at least two of them have to be non-zero. In Figure 13 the UHF PD spectrum of a rod-plane PD source is shown together with some calculated cavity resonances (values of *m, n, p* are given in the boxes). The measured cavity resonances show fairly good agreement with the calculated ones.

4.3 UHF PD SIGNAL ATTENUATION CHARACTERISTICS OF DIFFERENT MATERIALS AND STRUCTURES

The subject of this investigation is the basic impact of damping and alteration of UHF PD signals, traveling through different insulating materials and whole structures, which make up large parts of power transformers. The goal was to get an integral indication on how strong and in which way the UHF PD pulses are affected through these generic structures. With the experiments dominantly existent materials and structures within transformers were modeled. These materials and structures respectively have been 8.4 cm pressboard, a 0.5 cm gap in a metal shielding and a sector of a disc winding.

An important aspect of the tests was that always one and the same UHF PD pulse was measured with two independent disc-sensors. The whole propagation paths, disc-sensors and connecting cables were as similar and symmetric as possible. The impact of a structure put in one propagation path can consequently be analyzed directly through comparison with the second measured signal. On one hand the measured UHF PD time signals and their spectra and, on the other hand, the signal energy of the pulses was used for comparisons.

The laboratory setup basically contained a half-closed metallic test tank (1.0 m x 0.5 m x 0.5 m), a needle-sphere PD source, two identical disc-sensors (see Figure 13 for schematics) and a transient recorder with an analogue bandwidth of 3 GHz. No additional amplification was used. A metal wall between them electromagnetically decoupled the two sensors. This metal wall divided the closed half of the tank in two sections, with one sensor in every part (Figure 14).

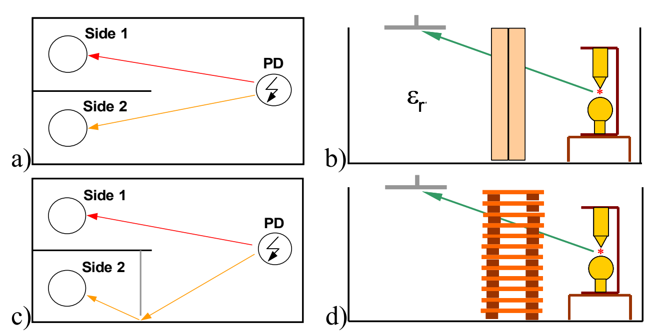

Figure 14. Schematics of the 2-path test setup: a) top view of the two-sided experimental setup with half-closed test tank (1.0x0.5x0.5) m^3, two disc-sensors and needle-sphere PD source; b) front view of the setup with 8.4 cm pressboard in 'side 2'; c) top view of the setup with a 0.5 cm gap in a metal plate in 'side 2'; d) front view of the setup with stacked parts of a disc-winding in 'side 2' (with gaps of 0.5 cm width within the disc-winding).

This so called '2-path-arrangement' offers the great advantage to independently measure one and the same UHF PD pulse simultaneously on two sensors.

Prior to the analysis of different materials and structures, reference measurements with the solely oil-filled '2-path-arrangement' were carried out. In this case it could be examined to which degree the two measured signals resemble each other, when they should ideally be identical, due to the fact of two identical propagation paths. The energy content of both pulses was calculated and compared. Since throughout the experiments 'side 1' remained unchanged (see Figure 14) – the calculated signal energy of 'side 1' acted as the reference value. The mean value for the pulse energy attenuation in the reference `'oil-oil' test without any barrier on ‘side 2’ was 4.27 % (-0.19dB) with a standard deviation of approximately 4.36 % in a series of seven measurements (ranging from 1.8 – 3.7 pC).

To simulate a huge amount of solid insulation material in the propagation path of an UHF PD signal two pieces of thick pressboard, with dimensions of (500 x 247 x 42) mm^3, were used and put into 'side 2', as shown in Figure 13 b). Investigation of a two-channel measurement of a 2.7 pC UHF PD pulse revealed light attenuation. Comparing the amplitudes of the un-attenuated and attenuated signal in time domain (Figure 15) a difference in the maximum pulse amplitudes (here from around 5 mV to 4 mV for the positive peek) is visible. Concerning the signal energy of the pulses, an average attenuation of 34.46 % (-1.83 dB) was recognized for the 8.4 cm thick pressboard. The standard deviation was 4.28 % in seven measurements (ranging from 2.7 – 6.9 pC). Due to the pressboard the signals featured a slight time shift of about 200 – 300 ps. This effect on the UHF signal was expected, since the permittivity of the pressboard (ε_r around 3.5) is higher than that of oil (ε_r around 2.2) resulting in a reduced propagation velocity for the electromagnetic waves within the pressboard.

The investigation with a 0.5 cm gap in a metal plate was conducted to examine the impact of metallic structures with a certain aperture as e.g. the gap between high and low voltage winding (which is certainly in the range of several centimetres for power transformers) or passages through grounded components within a transformer, when no line-of-sight between source and sensor is provided. The electromagnetic waves radiated from the PD cannot propagate through the metal plate, but have to reach the sensor of 'side 2' by mechanisms of reflection or diffraction. Figure 14 c) illustrates the experimental configuration as well as a possible reflected path. The experimental results showed an attenuation and delay. The sensor behind the metal plate was clearly responding later (delays ranging from 2.9 -5 ns). The corresponding spectra showed stronger differences in the higher frequency ranges (600 – 840 MHz and 1.35 – 1.55 GHz) than observed before with pressboard. The average attenuation of the pulse energies was 46.31 % (-2.70 dB) in a series of fourteen measurements (ranging from 1.1 – 6.0 pC) with an increased standard deviation of 8.30 %.

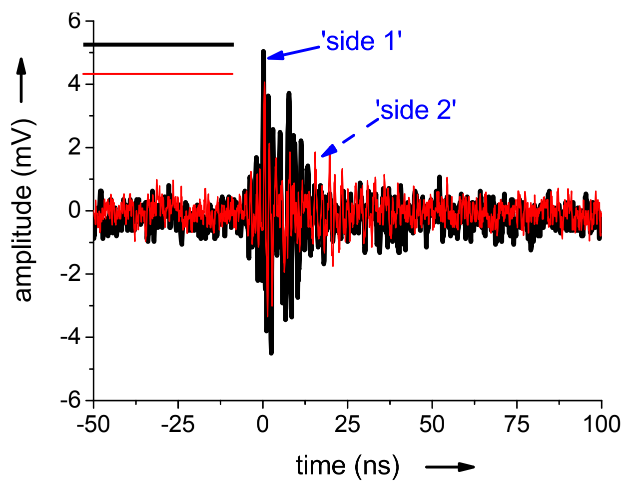

Figure 15. UHF PD signals of a needle-sphere PD-source in oil up to 3 GHz (bold line: 'side 1' - oil path; thin red line: 'side 2' - path included pressboard; apparent charge of 2.7 pC).

The last experimental setup included a part of a disc winding in 'side 2' (Figure 14 d)). The disc-windings interaction with UHF PD signals, which are propagating inclined through it, were studied. Due to the fact that the winding comprises metal (copper), pressboard spacers and paper a combination of the earlier observed effects of frequency-dependent attenuation and delayed detection were recognized (time delay again approximately 200 – 300 ps). The average attenuation of the described disc-winding investigation was 38.25 % (-2.09 dB) in eleven measurements (ranging from 2.1 – 7.1 pC) with a standard deviation of 8.87 %.

Summarizing the three experiments leads to the assumption that UHF PD signals can propagate within the whole transformer with comparatively low attenuation factors. For PD occurring within windings either a propagation path in the gap of e.g. high and low voltage winding or even through a disc winding is possible. The approximate average values of the observed attenuation factors were:

- 34 % (or 1.8 dB) for the pressboard (thickness 8.4 cm)
- 46 % (or 2.7 dB) for the 0.5 cm gap in a metal plate
- 38 % (or 2.1 dB) for the sector of a disc winding.

Recent UHF attenuation measurements on 220 MVA single-phase autotransformers showed attenuation magnitudes (for e.g. a propagation path through complete HV/LV-windings etc.) [19] comparable to expected attenuation factors of the investigated generic structures. The attenuation of UHF signals within the transformer varied there between 1 and 6 dB/m, depending on the location and therewith the propagation path of the UHF signals.

4.4 CASE STUDIES

4.4.1 PD ACCEPTANCE TEST IN SHIELDED LABORATORY

Performing the PD acceptance test in a shielded laboratory on a 3-phase autotransformer (450 MVA, 400 kV; dimensions greater than (10m x 3.5mx 4m)) simultaneous electric PD measurements according to IEC 60270 and UHF PD measurements have been carried out [13]. The UHF sensor was inserted in an oil valve at the bottom of the tank and connected to a transient recorder with an analog bandwidth of 3 GHz without any amplifiers. The electric PD measurements showed PD activity on low-voltage bushings of two phases up to 70 pC. Additionally UHF PD pulses with frequency components up to 600 MHz have been recorded. A further proving aspect has been that UHF signals have been detectable for UHF sensor insertion depth from 10 mm inside the tank to 20 mm outside of it (with regard to the inner tank wall) before fading away when pulling out the sensor further.

The geometrical distance from the low-voltage bushings to the inserted UHF probe was approximately 10 meters. Nevertheless this low-level PD was detectable with the UHF sensor; hence the resulting UHF attenuation within the active part of the transformer is sufficiently low. The final internal PD was not investigated further, since the PD was below acceptance level and therefore the transformer did pass the Factory Acceptance Test.

4.4.2 ON-SITE AND ON-LINE UHF PD MEASUREMENTS

After indication of PD by means of dissolved gas analysis on-site PD measurements were performed on a 200 MVA single-phase transformer over a period of several months. An electric PD measurement revealed levels up to 600 pC during an offline applied voltage test. For the carried out electromagnetic on-line UHF measurements, a disc-shaped UHF sensor was applied [13]. Again a transient recorder with an analogue bandwidth of 3 GHz and no amplification was used for recording of the UHF signals. The measurements featured very low noise levels. Figure 16 shows an on-line recorded UHF signal with its corresponding spectrum.

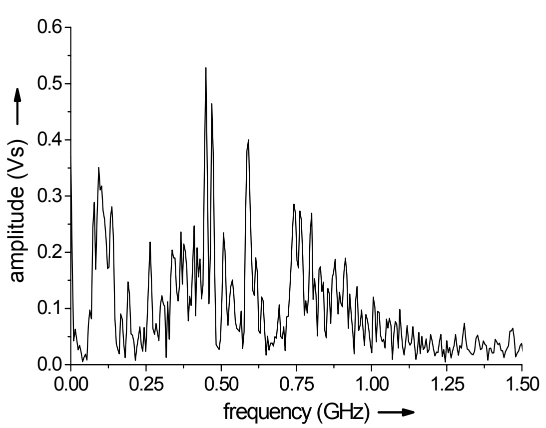

Figure 16. UHF PD spectrum of an on-line recorded UHF PD signal on a 200 MVA single-phase transformer.

Judging from the high frequency components up to 750 MHz – 1 GHz the UHF pulses were regarded as true internal PD pulses. Additionally the UHF PD pulses could be used to enhance acoustic PD measurements with an UHF-triggered acoustic averaging to locate PD [11]. Thus the hydrogen and electric PD measurements have been verified with sensitive UHF PD measurement on-site. Finally the acoustic location result was verified from the transformer manufacturer to be a "known suspicious position".

5 CONCLUSION

Unconventional electromagnetic (UHF) PD measurement applied on-site offers the great advantage to be more immune against disturbances than PD-measurement according to IEC 60270. Examples for GIS, cable accessories and oil-paper insulated power transformers show the improved PD detection and localization. Localization in GIS can be done both in the time and frequency-domain. The latter allows a very cost-efficient measurement.

Also, condition assessment of cable connectors can be performed on-site and on-line by means of UHF PD measurement. A metallic sleeve equipped with monopole antennas is clamped around the plug-in connector to detect electromagnetic waves emitted from PD within the connector. Thus, a sensitive PD measurement even in noisy environment is possible.

UHF PD signals can be decoupled from the inner of transformer tanks by means of sensitive UHF sensors, which could be applied in service through a drain valve. The spectra of these signals reflect cavity resonances of the tank. Experimental results regarding the sensitivity furthermore demonstrate a moderate attenuation of the UHF PD pulses within the presence of solid insulation or structures inside transformers. UHF PD pulse propagation even through disc-windings seems possible. On-line UHF measurements and laboratory experiments on power transformers featured very low noise levels and confirmed the high UHF PD detection sensitivity.

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