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Electromagnetic (UHF) PD Diagnosis of GIS, Cable Accessories and Oil-paper Insulated Power Transformers for Improved PD Detection and Localization

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SUMMARY

The paper presents several methods to increase the detection threshold and to improve the localization accuracy of PD by means of non-conventional UHF PD measurement.

A simple and commonly used way to locate PD in GIS is the measurement in time domain (time-of-flight). The time difference between the arrivals of the PD impulse on two UHF sensors is used for localization. The new developed method presented here uses the frequency domain. 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. This new method allows a more cost-effective localisation of PD in GIS.

On-site PD measurements are made at cable connectors, while the cable is in service. A barrel sleeve, acting as an electromagnetic screen, is clamped around the plug-in connector. Inside the sleeve there are monopole antennas to detect electromagnetic waves emitted from PD within the connector. Thus a sensitive PD measurement even in noisy environment is possible. PD-measurements in an unshielded laboratory were performed on several 45 kV cable connectors. Connectors with stimulated PD emitted fast electromagnetic pulses whereas measurements on connectors without PD showed only slight background noise. So the detection of UHF PD signals constitutes a strong sign for internal PD activity.

For the decoupling of UHF PD signals from the inner of the tank of power transformer, sensitive UHF sensors, which could be applied through a drain valve, are shown in this contribution. Comparative investigations of PD in power transformers with the electromagnetic UHF and the acoustic method revealed a much lower damping of the UHF signals compared to acoustic signals. As a consequence, a significantly higher sensitivity especially for hidden PD defects could be reached with this method. Because of the sensitivity differences between the UHF and the acoustic signals an advantageous combination of the two methods is reasonable. By simple averaging of the acoustic signals triggered with sensitive UHF impulses, the denoising effect helps to identify and localize faults that are not detectable with acoustic single impulses. The important determination of the localization of the PD is managed by using acoustic signal travelling times in a mixed-acoustic (i.e. UHF-triggering) manner. Several on-site/on-line measurements as well as laboratory experiments given in the contribution show the advantages of the unconventional PD measuring methods using electromagnetic UHF-signals and acoustic ultra-sonic signals.

KEYWORDS

GIS, Cable Accessories, Power Transformers, On-site PD-Measurement, UHF, Condition Assessment

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1. INTRODUCTION

Different PD measuring techniques are using different physical peculiarities of the PD phenomenon e.g. electric currents (acc. 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 standard 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. In general two items are necessary regarding the PD – its level and its location. Having information of the PD origin is essential to assess e.g. the risk potential of the fault. It is of tremendous importance to know about the PD origin to plan and start maintenance / repair actions cost and time efficiently.

The advantages of the unconventional PD measuring methods are their wide immunity against external disturbing signals on-site, the fact that the sensors need no electrical connection to the high voltage circuit and the inherent possibility of a three dimensional determination of the failure location (localization of the PD) using arrival times of these signals. Corona as strongly interfering electrical process, has in contrary to the electric PD measurement method according to IEC 60270 acoustically no influence because of the measuring principle. The electromagnetic (UHF) technique offers very low noise levels since the transformer tank acts nearly like a Faraday cage shielding external PD signals effectively. Nonetheless, an up to now existing drawback of these methods is that no assured apparent charge information (electric level in pC) is delivered.

The application of these unconventional PD measuring methods and their interpretation will be presented in this contribution for GIS, cable accessories and power transformers.

2 GAS-INSULATED SWITCHGEAR (GIS)

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.

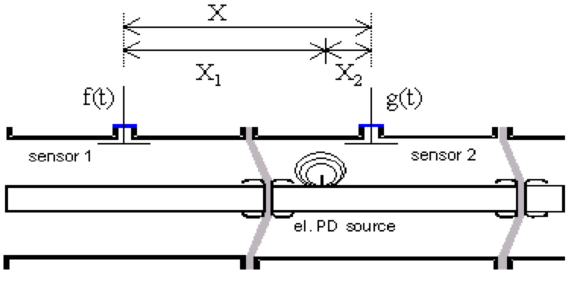

Fig. 1: Cross section of a GIS

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

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

$$\frac{\left|FFT\left[f(t-\Delta t)+g(t)\right]\right|}{\left|FFT\left[g(t)\right]\right|+\left|FFT\left[f(t)\right]\right|} = \left|\cos\left(\frac{\omega\cdot\Delta t}{2}\right)\right| \qquad (3)$$

2.1 Localization in Time Domain

The distance X_1 between PD source and UHF-sensor can be calculated with equation (1) in case the time difference (Δt) is known. X represents the distance between the sensors and c_0 is the propagation speed of the wave in the GIS ($c_0 = 0.3$ m/ns). The time difference is determined by the initial impulse steepness of the two signals [1]. If the initial start of the signal is not totally clear or there are different signal-to-noise ratios (SNR) of the two signals, the measurement of the time difference Δt is not easily detectable in all cases.

It is possible to reduce the necessary measurement equipment to a minimum by means of fast time-to-digital converters (resolution e.g. ~125ps). To localize cost effectively an electronic circuit was developed. Hereby a fast counter replaces the oscilloscope. The technique requires furthermore an analogue signal processing which converts the UHF-signal into digital start and stop commands. A well-proven method to determine the starting point of a signal is to investigate the power of the signal, which can be determined with power detectors. In the laboratory, accuracies better than 2ns can be achieved. The sensitivity of the system is sufficient to localize PD with a charge below 5 pC. Further investigations on-site have to prove the sensitivity under real conditions.

2.2 Localization in Frequency Domain by means of Interference Measurement

Another method to localize PD in GIS is the measurement in the frequency domain. A measurement procedure with a spectrum analyser 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 (equ. 2) of the received signals.

2.2.1 Measurement Procedure

To visualise the interference phenomena, it is not sufficient to make only one measurement. There are three power spectrums needed, which are compared in a characteristic way. The power spectrum is the absolute value of the complex FFT. The three power spectrums are obtained from Sensor 1 (equ. 4), Sensor 2 (equ. 5) and the added signal of Sensor 1 and 2 (equ. 6) with a conventional spectrum analyser. The last signal is obtained by means of a RF power splitter. These three signals are combined in equation 3. The time difference (Δt) can be calculated with the resulting cosine function in case of f(t) = g(t). This cosine function has equidistant minima (Fig. 2), which can be interpreted as interference phenomena.

$$F(\omega) = \left| FFT[f(t)] \right| \quad (4) \qquad G(\omega) = \left| FFT[g(t)] \right| \quad (5) \qquad H(\omega) = \left| FFT[g(t) + f(t - \Delta t)] \right| \quad (6)$$

2.2.2 Requirements

Two related signals are required to obtain useful results from equation (3). Current studies show that a magnitude difference is not critical if the nature of both signals is similar [2]. To keep the characteristics of both signals similar, the effect of dispersion should be kept as small as possible. The group velocity (v_g) of the TE- / TM-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 [3]. One requirement for a successful result is a sensitive measurement in this frequency range. All other effects influencing the signal within the GIS should be eliminated.

2.2.3 Localization of artificial PD-pulses

Localization of artificial PD-pulses was performed in a 9 m long 550 kV laboratory GIS with or without termination at wave impedance. In this experimental set-up the connection cables to the UHF sensors are different in length to increase the absolute time difference Δt. The PD-source is a pulse generator with an antenna (with an equivalent magnitude according to IEC 60270 q = approx. 50 pC). The time difference (Δt) is measured in the time domain as Δt = 95.6 ns. The combined signal according to equ. 3 is shown in Fig.2. The interference phenomena can be seen clearly and are fitted by a cosine function. The best matching with the theoretical cosine function is at Δf = 10.54 MHz and so Δt can be calculated as Δt = 94.9 ns, which is in good agreement with the time domain measurement [2].

2.2.4 Interpretation of frequency domain measurements

With different GIS types and set-ups the interference phenomena are not always so clearly visible as in the above-presented example. In such a case, an objective method is necessary in order to fit the combined measurement with theoretical cosine functions of different Δt. The best correlation of the measured combined signal with the theoretical cosine function is determined by the calculation of the maximum cross-correlation. The theoretical function with the wanted Δt possesses the largest correlation and thus the value of the cross-correlation is at its maximum. In this way, also frequency domain localization where the interferences are not so clear is possible. Fig. 3 demonstrates this for a PD generated by a protrusion on the outer conductor of a 362 kV GIS. The best matching is in this case for Δt = 70.7 ns (time domain measurement reveals Δt = 73.5 ns).

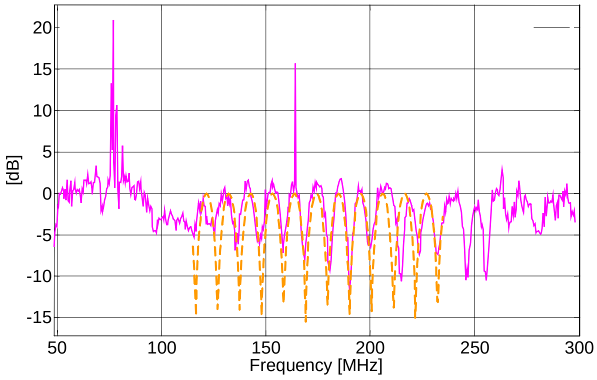

Fig. 2: Localization of calibrator pulses

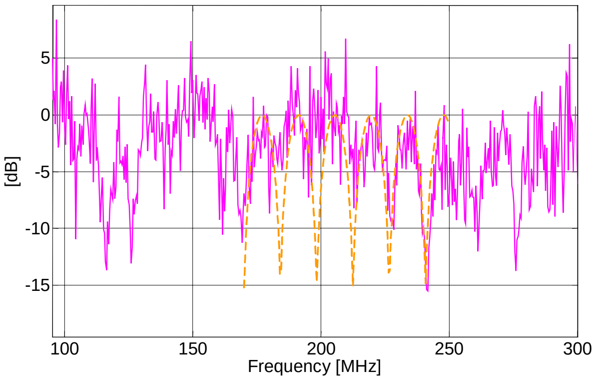

Fig. 3: Localization of PD in a 362 kV GIS

3 CABLE ACCESSORIES

Statistics show that most failures caused by internal fault in the insulation of cable systems occur in accessories, such as joints and terminations [4]. This part of the paper discusses the experience in on-site on-line UHF PD diagnostics of MV cable terminations.

3.1 Motivation for On-site Measurements

The goal of condition monitoring of cable accessories is to predict failures before they occur. Those accessories that are about to fail can then be replaced, thereby reducing the risk of cable system failures. PD activity detected within the accessory is a clear signal for replacement. To detect such an activity under conditions of on-site on-line testing, UHF PD diagnosis principle can be deployed. This method is based on sensing the electromagnetic emissions from discharge sites in the insulation. The coupling sensors should be placed as close as possible to the test object and effectively screened against external interferences.

3.2 Test Set-up and Results

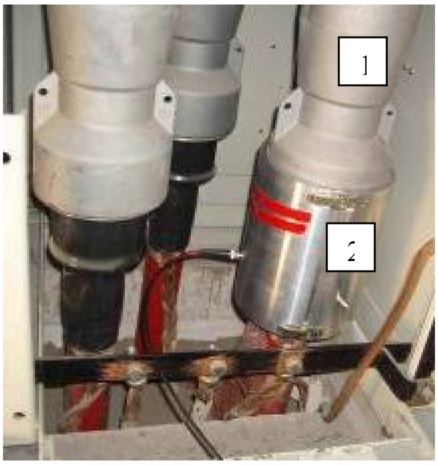

Fig. 4: Test set-up consisting of (1) plug-in connector and (2) metallic barrel sleeve with antennas

On-site PD measurements are made at cable termination and in the manhole of GIS, while the cable is in service. A barrel sleeve, acting as an electromagnetic screen, is clamped around the plug-in connector (size 4, up to 72 kV) as shown in Fig. 4. Inside of the sleeve there are three 5 cm long monopole antennas, each placed 1-2 cm above the cable surface and oriented at a tangent to the cable cross-section. Antennas are shifted by 120° from each other to embrace the whole circumference of the test object. The measured signal from the antenna via a 40 dB pre-amplifier (in a frequency range from 1 to 1000 MHz) is fed to the digital oscilloscope (LeCroy ProWave 7300).

The calibration of the UHF method in terms of amount of charge is impossible, but comparative PD measurements were performed on the very identical test set-up, assembled in laboratory, using both the UHF method and the conventional method according to IEC60270. It was done to establish the maximal sensitivity of the UHF method. Raising the applied voltage controlled the level of PD. A sensitivity of 4 pC turned out to be detectable by the UHF method.

PD-measurements in an unshielded laboratory were performed on several 45 kV cable connectors. Connectors with stimulated PD emitted fast electromagnetic pulses whereas measurements on connectors without PD showed only slight background noise. So the detection of UHF PD signals constitutes a strong sign for internal PD activity.

Fig. 5 shows such a typical fast pulse signal picked up on a connector with PD. The frequency spectrum of this pulse is plotted in Fig. 6. Besides some broadcast and GSM frequency spikes, there are several other high frequency components that indicate presence of PD activity [5].

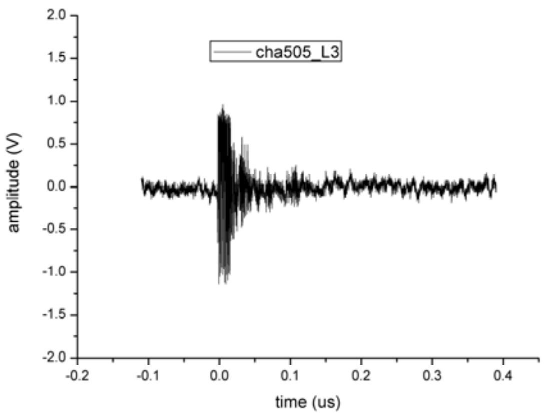

Fig. 5: Typical fast pulse emitted by some connectors and acquired with a bandwidth of 3GHz

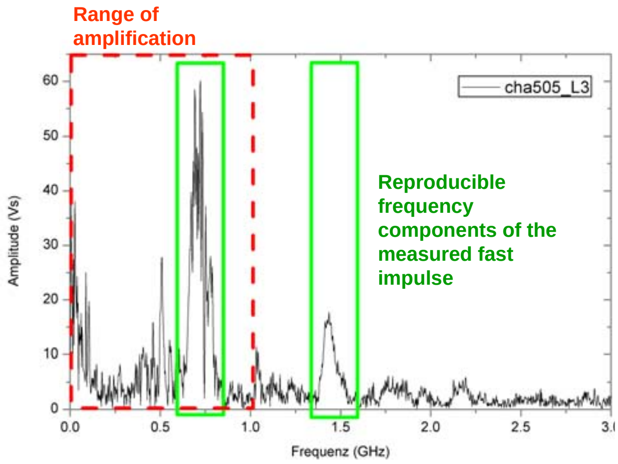

Fig. 6: Frequency spectrum of PD-pulse

4 POWER TRANSFORMERS

4.1 Sensors for Electromagnetic and Acoustic PD-Detection

For the decoupling of UHF PD signals from the inner of the transformer tank capacitive UHF sensors can be installed through the drain valve. Different types of sensors - monopole-formed and disc-shaped – can be distinguished. While for laboratory test both types have been used, only the disc-shaped sensor was applied in on-line measurements (Figure 7 a). For the acquisition of acoustic PD signals normally piezoelectric sensors are applied. They provide a conversion of incoming mechanical pressure waves (emitted from the PD) into electrical signals. These sensors can be conveniently mounted on the outside of the tank wall. The acoustic bandwidth normally lies within 10 – 300 kHz as a result of noise suppression for deeper frequency ranges and increasing damping for higher frequencies. As mentioned, this non-destructive application of the sensors for both methods can be managed while the transformer stays in full service, since there is no electrical connection needed to the high voltage circuit.

4.2 Detection and Localization

Concerning PD measurements two main tasks are encountered. First is to provide evidence of PD (*detection*) as sensitive as possible in terms of a decision “PD-yes/no”. Second is the, in many respects important, determination of the PD location (*localization*). The on-site resulting detection sensitivity for PD may be hampered in the conventional electric case while the mentioned unconventional methods – electromagnetic (UHF) and acoustic – do not suffer from external disturbances. Besides applying the two unconventional methods separately an advantageous combination of them is also reasonable for an optimized detection and localization.

Regarding the PD localization on the basis of acoustic arrival time, three different approaches for the system of nonlinear observation equations could be distinguished. Depending on whether mixed-acoustic (i.e. electric or electromagnetic triggering) or all-acoustic (acoustic triggering) measurements are used, the equations have three (space coordinates (x, y, z) of the PD) or four unknowns (an additionally unknown temporal origin). A new approach within the acoustic signal processing works with pseudo-times, allowing the usage of robust direct GPS (Global Positioning System) solvers instead of the previously used iterative algorithms [6]. In the presence of inevitable measuring errors, sensitivity limits or wrongly assumed acoustic propagation velocities much more stable results were featured by the direct solver. Another important part of the localization procedure is a correct objective arrival time determination. Here good experiences have been gathered with signal-energy based criteria.

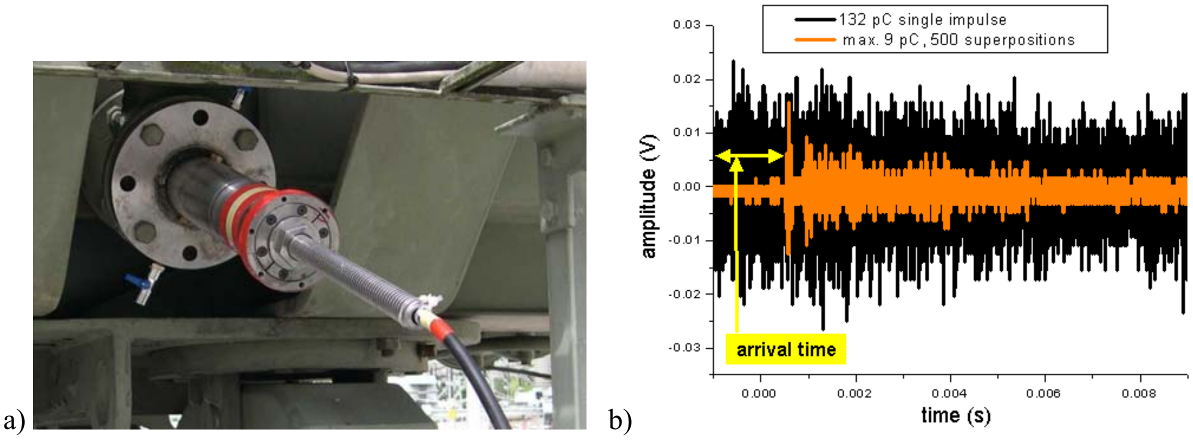

Fig. 7: a) installed UHF-sensor at drain valve; b) comparison of a 132 pC single impulse and an UHF-triggered averaging signal with 500 superposition of maximum 9 pC (same experimental arrangement and sensor position).

4.3 Sensitivity Considerations and Examples

4.3.1 UHF-induced Sensitivity Enhancement for Acoustic PD Measurements

Increasing the signal/noise-ratio or in other words denoising signals with an averaging process (continuously form the mean value) has long been known and used. To be successfulb a stable trigger is required, signal and noise should be uncorrelated and the noise is supposed to be white (i.e. has a constant spectral density in the investigated frequency range). In terms of PD measurements and the goal to denoise acoustic signals e.g. to quantify their arrival times hidden in the noise, one needs to have a physical signal related to the PD with a significantly higher sensitivity than the acoustic one. Here, electromagnetic UHF PD signals have proven their applicability.

During the averaging process, the noise contained in the acoustic signal tends towards its statistic mean value, which is zero if white noise is assumed. The acoustic signal itself is superimposed constructively and the presence of an acoustic signal with stable relation to the UHF trigger can be verified with high sensitivity. The theoretically maximum signal/noise-ratio gain is $N^{0.5}$, where N is the number of superposition. Fig. 7 b) shows a comparison of a single acoustic PD impulse of a 132 pC with no clearly observable information and an UHF-triggered averaged signal with 500 superimpositions of maximum 9 pC where a clear impulse is visible (same experimental arrangement, same sensor position) [7]. Another important aspect of UHF-acoustic coupled measurements lies within the increased plausibility of the decision for or against PD activity: Mechanical noise has typically no inner electromagnetic signal, while electromagnetic noise could not create mechanical signals with a stable phase relation needed to be existent for showing a signal after an averaging process.

Regarding the study of the general UHF signal behavior inside of metal enclosures, experimental measurements in a small test tank with the dimensions of 1,0x0,5x0,5 m were arranged. A monopole with a 3 dB attenuation cell was used for decoupling the UHF PD impulses of a rod-plane PD source. PD of apparent charges down to 50 pC was measured with a transient recorder (analogue bandwidth 1 GHz) without any amplification. Due to the fact that the high-frequency signal was reflected several times inside the test tank, measured signals usually had a long duration up to 100 ns (Figure 8 a)).

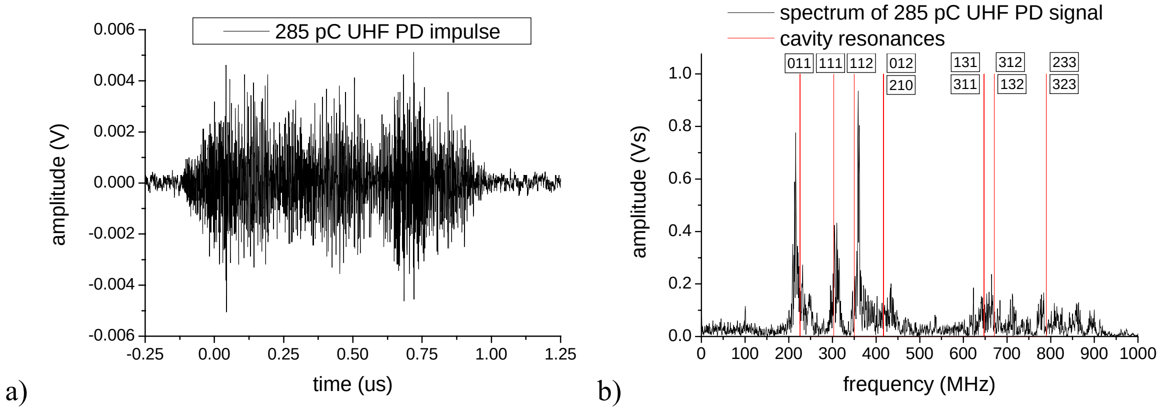

Fig. 8: a) UHF PD impulse (apparent charge 285 pC); b) corresponding UHF PD spectrum with some dominant cavity resonances

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

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

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 8 b) the spectrum corresponding to the UHF time signal of Figure 8 a) is shown together with some cavity resonances (values of m, n, p are given in the boxes). The revealed cavity resonances possibly make up the basis for advantageous narrow-band measurements.

4.3.2 Laboratory UHF-acoustic Localization case study

The experimental configuration consists of a coil at high voltage surrounded by two pressboard cylinders immersed in an oil-filled transformer tank with a stimulated PD on the inner side of the coil. The applied UHF sensor was a monopole antenna inserted through a drain valve with no amplification for the signal. On the outside of the tank, four piezo-electric acoustic sensors and 60 dB amplifiers were attached to capture the acoustic PD signals. A comparison of acoustic PD signals of 575 pC (single impulse) and 9 pC (averaged signals with 500 superposition) concerning their amplitude, arrival time and the resulting location accuracy was drawn. The noise floor of the single impulse measurement (575 pC) was about 35 mV and could be diminished to about 2.5 mV in the averaged signal. With maximum impulse amplitude of approximately 12.5 mV of the superposed impulse (comparable to Figure 7 b)) this averaged impulse is completely hidden in the noise floor of a single measurement. The resulting acoustic sensitivity gain due to the UHF triggering is conservatively estimated to a factor 10 in this experiment (PD around 100 pC might be visible on sensor positions not used). The computed PD localizations featured a spatial deviation from the PD origin of 1.6 cm (575 pC case) and 10.4 cm (9 pC case).

4.3.3 On-line UHF-acoustic PD Measurements on a 200 MVA, 380/220 kV-single-phase Transformer

Over a period of several months, on-site PD measurements were performed at a 200 MVA single-phase transformer whose gas-in-oil diagnosis indicated PD. An electric PD measurement revealed levels up to 600 pC during an offline applied voltage test. For the carried out electromagnetic UHF measurements, a disc-shaped UHF sensor was applied (Figure 7 a)). Again no amplification was used for the UHF signals (transient recorder had an analogue bandwidth of 3 GHz). Figure 9 shows an online-recorded UHF signal with its corresponding spectrum. Comparative investigations of PD in power transformers with the electromagnetic UHF and the acoustic method revealed a very moderate damping of the UHF signals in oil and in the solid insulations, in contrast to the resulting attenuation of the acoustic signals. As a consequence, a significantly higher sensitivity especially for hidden PD defects could be reached with the UHF method. Acoustic PD localization results, gathered over several independent measurements with changing sensor positions, matched very well [6].

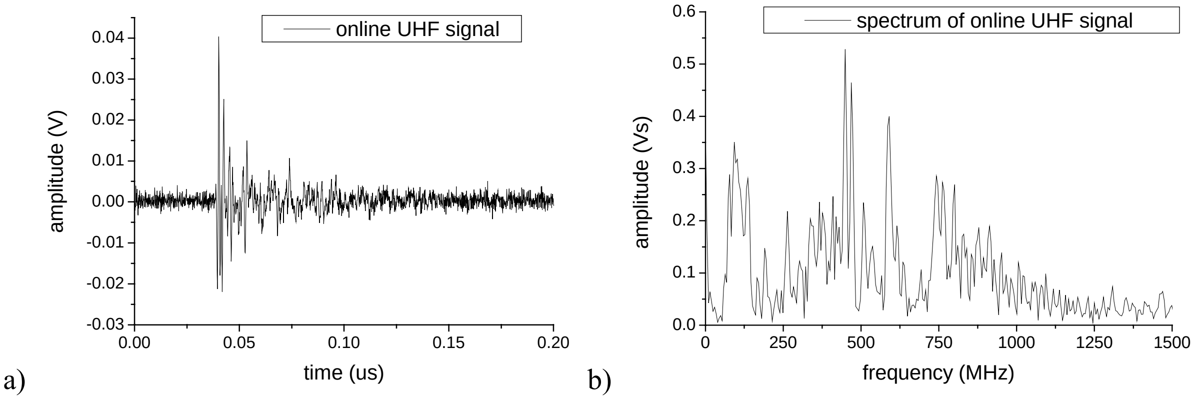

Fig. 9: a) UHF PD signal recorded on-line on a 200 MVA single-phase transformer; b) corresponding UHF PD spectrum

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. Connectors with stimulated PD emitted UHF-pulses. In case of PD-free connectors only slight background noise is observable.

UHF PD signals can be decoupled from the inner of the transformer tank 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 demonstrate the advantages of the UHF signals regarding sensitivity within the presence of solid insulation. While the acoustic detection limit might be around 100 pC in an experimental set-up it was possible to locate 9 pC acoustically quite exactly with the help of UHF signals. Hereby the UHF signal triggers the acquisition of the acoustic signals. By means of averaging of the acoustic signals the signal to noise ratio can be increased dramatically. On-line UHF measurements on power transformers featured very low noise levels. So far difficulties regarding sensitive triggering on UHF signals due to presence of external UHF signals e.g. corona or telecommunication channels, could be prevented.

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