Improvement of acoustic detection and localization accuracy by sensitive electromagnetic PD measurements under oil in the UHF range

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Abstract: Partial discharge (PD) diagnosis for large power transformers as one of the most powerful tools to evaluate insulating quality and characteristics should be carried out as permanent monitoring or onsite measurements with adequate sensitivity. This allows conditioned based maintenance strategies, serves asset appraisements and permits continuous risk assessment. Online/onsite electric PD measuring procedures according to the IEC60270 standard so far show a limited reachable sensitivity e.g. caused by corona. Since PD also appear as source of mechanical waves in the ultra-sonic range and electromagnetic waves up to the UHF (ultra high frequencies) range additional acoustic or electromagnetic measurements are possible and helpful in online/onsite measurements.

Comparative investigations with the acoustic and the UHF method revealed a very moderate damping of the UHF signals in oil and in the solid insulations in contrast to resulting attenuation of the acoustic signals. Thus a significantly higher sensitivity especially for hidden PD defects could be reached with the UHF method. Sensitive electromagnetic UHF PD measurements help to identify and localize faults which are not detectable with acoustic single impulses by simple averaging of the acoustic signals. Furthermore broad-band investigations of UHF spectra revealed cavity resonances which possibly make up the basis for advantageous narrow-band measurements.

INTRODUCTION

Full knowledge of PD activity of a oil/paper-insulated transformer provides an informative basis to judge its insulation condition. Presently PD diagnosis is desired not just in test bays but with an increasing demand for aged equipment in service supporting aging estimations. Generally main information about PD could be its level, type and location. For transformers where e.g. a dissolved gas in oil analysis gives PD indication an online investigation using unconventional methods (acoustic and UHF) can give valuable information. Normally the necessary efforts for such measurements are not as high as for offline electric PD measurements due to the energized state of the transformer in the online case.

Despite all-acoustic PD diagnosis including PD location can be managed [1] the key problem in online measurements regarding PD positioning is a lack of enough acoustic impulses simultaneously recorded which is certainly caused by the high acoustic damping. Hence there are not enough arrival times to render a location. Mixed-acoustic methods like a UHF-acoustic combination could help to overcome this constraint and improve the acoustic detection and localization accuracy significantly at the same time.

GENERAL ASPECTS OF ACOUSTIC AND ELECTROMAGNETIC PD MEASUREMENTS

Some outstanding advantages of the acoustic method are its immunity against corona and the fact that piezoelectric sensors can be conveniently mounted on the outside of the tank wall while the transformer stays in full service. No electrical connection to high voltage circuit is needed. The used acoustic bandwidth normally lies within 10 – 300 kHz as a result of strong noise for deeper frequency ranges and increasing frequency-dependent damping for higher frequencies.

The electromagnetic (UHF) technique offers very low noise levels since the transformer tank acts nearly like a Faraday cage shielding external PD signals effectively. The appropriate UHF sensors can be applied online through a standardized oil valve and very low signal damping in solid insulation and oil is observed. Unfortunately so far no assured apparent charge information (electric level in pC) is delivered from the UHF or the acoustic method.

LABORATORY ELECTROMAGENTIC PD MEASUREMENTS (UHF RANGE)

To study signal behavior and possible matched sensors experimental UHF measurements in a small test tank (Figure 1) were arranged.

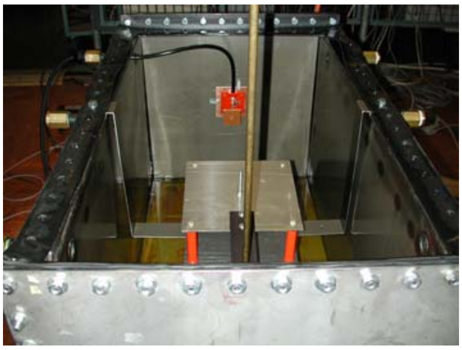

Fig.1: Test tank (1.0x0.5x0.5)m here without cover, prototype monopole (upper middle) and rod-plane PD source (middle of the photo)

A prototype monopole with a 3 dB attenuation cell (Figure 2) was used for decoupling the UHF PD signals of a rod-plane PD source. PD of electric level down to 50 pC were 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 3).

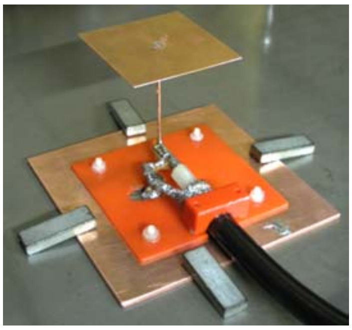

Fig.2: Prototype monopole with 3 dB attenuation cell

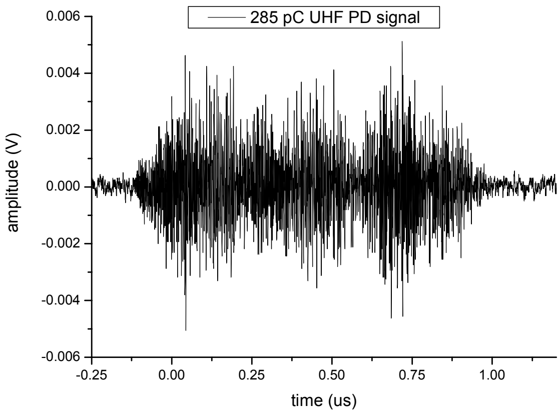

Fig. 3: UHF PD signal (electric level 285 pC)

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

$$f_{nmp} = \frac{c_0}{2\sqrt{\varepsilon_r}} \sqrt{\left(\frac{m}{a}\right)^2 + \left(\frac{n}{b}\right)^2 + \left(\frac{p}{c}\right)^2} \quad (1)$$

defines 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 in whole numbers and at least two have to be non-zero. In Figure 4 the frequency domain signal corresponding to the UHF time signal of Figure 3 is shown together with some cavity resonances (values of *m*, *n*, *p* are given in the boxes).

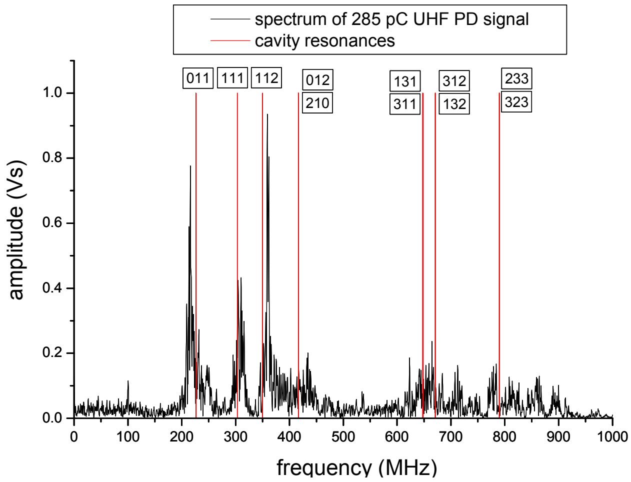

Fig. 4: UHF PD frequency domain signal with some cavity resonances (electric level 285 pC)

UHF-ACOUSTIC MEASUREMENTS FOR PD POSITIONING

Averaging of acoustic PD signals with UHF trigger

Starting an averaging process of noisy signals to increase the signal/noise-ratio or in other words denoise the signals has long been known. Indeed a stable trigger is required to be successful. In terms of PD measurements and the goal to denoise acoustic signals to e.g. quantify their arrival times hidden in the noise one needs to have a physical signal related to the PD with a higher sensitivity than the acoustic ones. The UHF PD signal has proven its applicability.

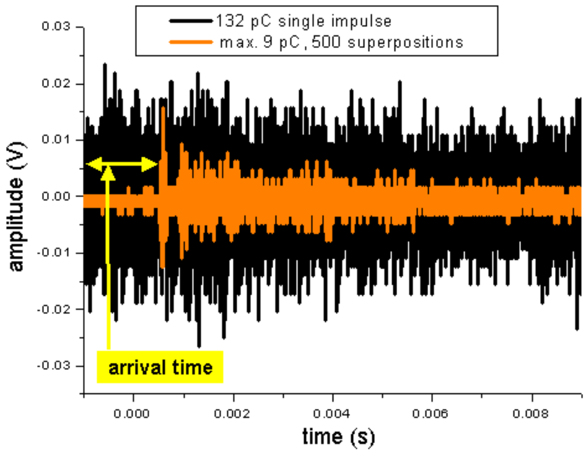

Fig. 5: Comparison of a 132 pC single impulse and 500 superpositions of maximum 9 pC

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 a 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 superpositions. Figure 5 shows a comparison of a single acoustic impulse of a 132 pC PD with no clearly observable information and 500 super-impositions of maximum 9 pC where a clear impulse is visible (same experimental arrangement, same sensor position).

Such a combination of two PD signals of different type is well-known in the test bays where usually the sensitive electric PD signal is combined with the acoustic signals to locate PD. With the UHF signal a sensitive trigger for acoustic measurements can be used online and the averaging procedure can be adapted.

4 channel PD positioning with UHF triggering (a 575 pC / 9 pC comparison)

The experimental configuration shown in Figure 6 contains a coil at high voltage surrounded by two pressboard cylinders with a stimulated PD at the inner side of the coil immersed in a oil-filled transformer tank. The applied UHF sensor was a monopole antenna comparable to Figure 2. It was inserted through a drain valve (Figure 2 up left) using an apparatus similar to Figure 10. On the outside of the tank four piezo-electric acoustic sensors and 60 dB amplifiers were attached to capture the acoustic PD signals.

Fig. 6: Coil at high voltage with stimulated PD at known position surrounded by two pressboard cylinders

In the following a comparison of acoustic PD signals of 575 pC (single impulse) and 9 pC (averaged signals 500 superpositions) concerning their amplitude, arrival time and the resulting location accuracy is discussed. Figure 7 pictures the acoustic PD signal (575 pC) of sensor 2 with a noise floor about 0.035 V (the noise floor is visible before the first impulse starts). The averaged signal of maximum 9 pC of the same signal is shown in Figure 8. The noise floor has been diminished to about 0.0025 V and the maximum impulse amplitude is 0.0156 V. Hence this averaged impulse is completely hidden in the noise floor of single measurements. The acoustic measurements and the averaging were done by a transient recorder (analogue bandwidth 200 MHz).

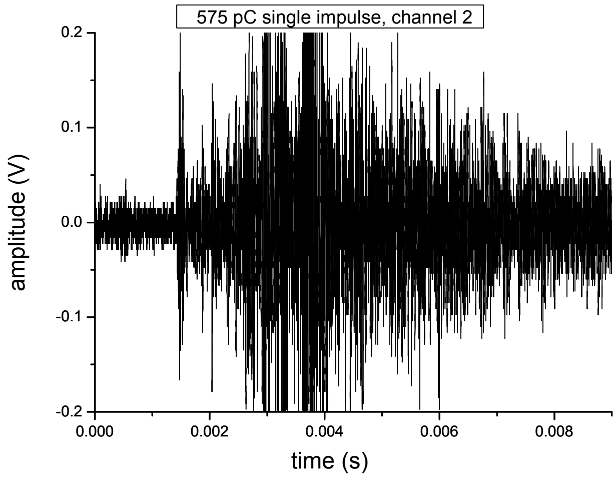

Fig. 7: acoustic single impulse of a 575 pC PD (noise floor about 0.035 V)

The averaged signal of sensor 1 of this experiment is used for the comparison in Figure 5. The corresponding arrival times for the single impulses as well as the averaged signals are given in Figure 9. They are compared to geometric arrival times determined by the spatial distance of the sensors to the PD. The arrival times of the strong single impulses can be determined automatically with an energy-based criteria [1] while the arrival times of the averaged signals are picked by an analyst (hand picking).

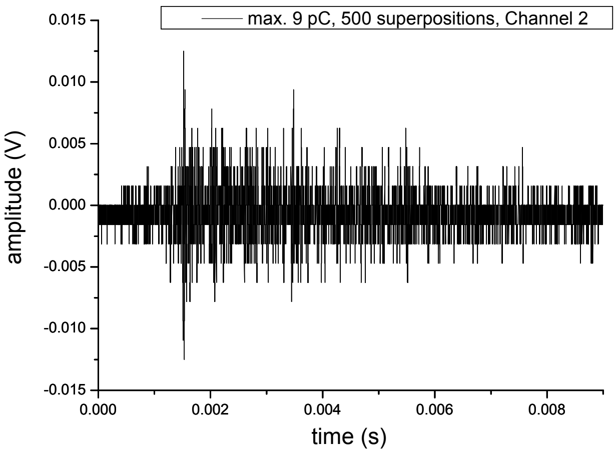

Fig. 8: 500 superpositions of maximum 9 pC (maximum impulse amplitude 0.0156 V, noise floor about 0.0025 V)

For the computation of the PD location with UHF triggered acoustic signals an mathematical model with 3 unknowns (space coordinates of the PD) can be used. Dealing with four sensor signals is an over-determined case normally solved iteratively. Nevertheless using an algorithmic special case new direct solvers which work with four unknowns (determined case in this experiment) can also be used [1]. The results of the PD positioning are given in Table 1 for the 575 pC and the 9 pC measurement respectively.

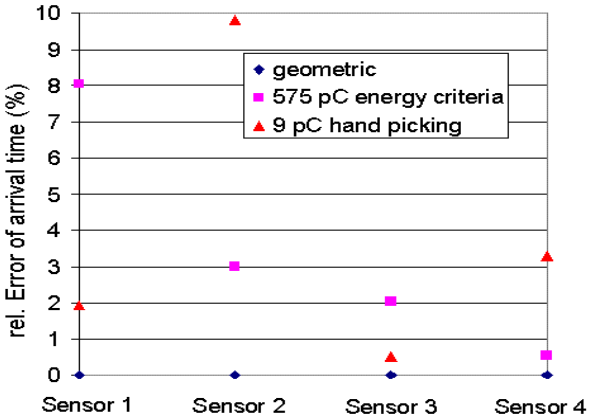

Fig. 9: Comparison of acoustic arrival time for the 575 pC and 9 pC measurements

The PD origin calculation with arrival times of the 575 pC case is quite exact (spatial deviation of 1.6 cm), while the PD position estimated with the averaging arrival times features a bigger error (spatial deviation of 10.4 cm).

	x [m]	y [m]	z [m]
PD position	0.93	0.52	0.85
575 pC measurement			
Calc. PD origin	0.925	0.535	0.854
Spatial deviation	1.6 cm		
Max. 9 pC averaging measurement			
Calc. PD origin	0.873	0.591	0.80
Spatial deviation	10.4 cm		

Tab. 1: PD positioning results of the 575 pC / max. 9 pC UHF-triggered acoustic PD measurements (direct calculation with 4 unknowns and 4 sensor signals)

ONLINE UHF-ACOUSTIC PD MEASUREMENT ON A 200MVA, 380/220KV-SINGLE-PHASE TRANSFORMER

The gas-in-oil diagnosis of the inspected 200 MVA single-phase transformer indicated PD. Several all-acoustic measurements and one electric PD measurement (levels up to 600 pC were revealed) during an offline applied voltage test were performed to get a better understanding of the PD failure existing [1]. The applied UHF sensor was of disc-shaped type (Figure 10/11) and its application was carried out in service. Again no amplification of the UHF signal was used and the full analogue bandwidth of 3 GHz of the transient recorder could be utilized. UHF signals were recorded even with the sensor a few centimeters inside the valve. Figure 12 shows an online recorded UHF signal which gave a stable trigger for the acoustic channels.

Fig. 10: A disc-shaped UHF-sensor for a standardized valve (DN 80) for online applications

Fig. 11 : The installed disc-shaped UHF-sensor for standardized valves (installed in service)

The corresponding frequency domain signal is depicted in Figure 13. It features higher contents up to approximately 1 GHz.

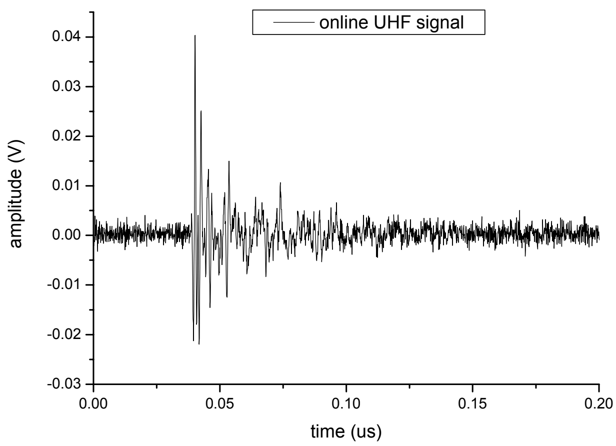

Fig. 12: UHF PD signal recorded online on a 200 MVA single-phase transformer

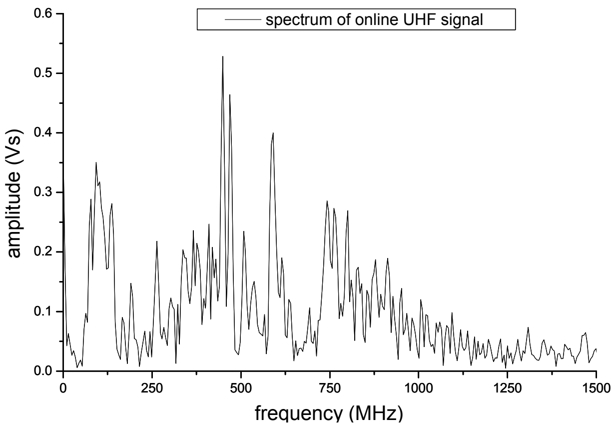

Fig. 13: UHF PD frequency domain signal corresponding to Figure 12

The UHF-triggered averaging of acoustic signals as explicated above seems to be possible at least on one channel (Figure 13). Unfortunately only a screen shot of the transient recorder can be presented due to a incorrect saving of the trace to disk. The PD source decayed shortly after the measurement of Figure 13 to a smaller level. Clear UHF signals were still detectable but probably the acoustic signals are even with denoising to small to be visible. For the smaller UHF signals the acoustic averaging only resulted in fairly flat lines. The UHF-acoustic measurement will be repeated soon to confirm the result.

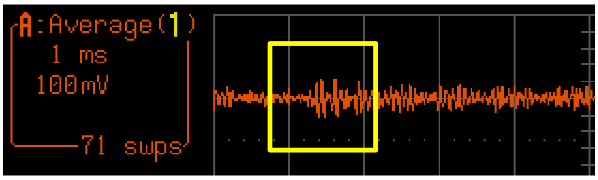

Fig. 13: Averaging of online UHF-triggered acoustic signals (71 superpositions) with highlighted signal beginning

CONCLUSION

Electromagnetic UHF signals emitted from PD inside a tank obviously have strong resonant character. Analytically calculated cavity resonances of a test tank bear resemblance to the peaks in the spectra of the PD.

Experimental results demonstrated the advantages of the UHF signals regarding sensitivity with the presence of solid insulation. While the acoustic detection limit might be around 100 pC in the experiment (depending on the sensor position) it was possible to locate 9 pC acoustically quite exact with the help of sensitive UHF signals. The UHF-triggered averaging of the acoustic signals results in a strong denoising making acoustic arrival times available.

Online UHF measurements featured very low noise levels and the sensor could be installed in service. UHF signals were detected without amplification. So far difficulties regarding sensitive triggering on UHF signals due to presence of external UHF signals e.g. corona or telecommunication channels could not be observed. This is probably in consequence of the disuse of amplification for UHF signals up to now and the decreasing sensor sensitivity for lower frequency ranges.

REFERENCES

[1] S. M. Markalous, S. Tenbohlen, K. Feser. New robust non-iterative algorithms for acoustic PD-localization in oil/paper-insulated transformers. *14th International Symposium on High Voltage*, Beijing, China, 2005