Location of PD Sources in Power Transformers by UHF and Acoustic Measurements

Sebastian Coenen
Siemens AG, TLM – Transformer Lifecycle Management
90461 Nürnberg, Germany

and **Stefan Tenbohlen**
Institute of Power Transmission and High Voltage Technology
Universität Stuttgart
70569 Stuttgart, Germany

ABSTRACT

The paper presents the experience of unconventional methods for partial discharge (PD) measurement to detect and localise PD sources in power transformers.

The UHF PD measurement method is usable as stand-alone measurement and as a supporting measurement for off- and on-line PD detection. The sensitivity of UHF PD measurements is sufficient and is normally not affected by external disturbances. Especially in noisy surrounding it might be a very helpful method to support other PD measurement techniques for example dissolved gas analysis and acoustic location of PD.

Propagation time of UHF signals can be used for geometrical PD location. The accuracy seems to be adequate to determine the phase limb where the PD is located. Additionally, different measurable UHF amplitudes support an estimation of the PD location. However, since transformers rarely possess more than three oil valves for installation of UHF probes, an additional acoustic measurement is usually required for location. Using the knowledge gained from the UHF location, acoustic sensors can be placed near to the PD source at the transformer tank. The paper explains first the fundamentals of PD measurements and PD source location and presents two case studies.

Index Terms - **Power transformer, partial discharges, On-site PD measurement, UHF method, acoustic PD location.**

1 INTRODUCTION

THE reliability of electrical energy networks depends on the quality and availability of primary electrical equipment such as power transformers. Local internal insulation failures can lead to catastrophic breakdowns and incur long outage and penalty costs. To avoid such risks, power transformers must be tested by several standard test procedure one of which is partial discharge test before acceptance and commissioning. Once installed it is costly to energise with e.g. induced test voltage or resonant sets. Results are often restricted by high site interference. Many users then rely on integrated detection methods such as the use of dissolved gases in oil.

The conventional, the UHF (UHF: Ultra High Frequency) and acoustic PD measurement method are using different physical phenomena of the PD activity, e.g. pulse current according to IEC 60270 [1], electromagnetic waves (300 MHz - 3 GHz) and acoustic wave (20 kHz - 1.5 MHz).

The electrical PD-measurement set-up according to IEC 60270 usually has sensitivity limitations for on-site/on-line measurements because of the noise level in field [2].

The so called UHF PD measuring method is based on the facts that PD under oil are very fast electrical processes and radiate electromagnetic waves with frequencies up to the ultrahigh range (UHF: 300 – 3000 MHz). UHF probes see Figure 1 and [3], can be inserted into the transformer during full operation through the oil filling valve.

Due to the moderately attenuated propagation of UHF waves inside the transformer tank, the sensitivity to electromagnetic wave detection is high [4]. As a result of shielding characteristics of the transformer tank against external electromagnetic waves, normally a clear decision can be made concerning the PD activity of the test object.

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Figure 1. UHF PD probe for standard oil filling valve (DN80).

When electrical or UHF PD measurements confirm PD activity, a three dimensional location of PD sources is the next step for risk evaluation of PD phenomena. With three space coordinates and a time dimension relating to a single PD event, four sensors are needed at least in order to locate the PD. UHF technology offers this possibility but access for most transformer designs is normally limited to three sensors or less. Because there is no limit in the number of piezo-electric acoustic sensors that can be mounted on transformer tanks, the acoustic measurements remains attractive for location purposes. However, acoustic sensors are normally more sensitive to external disturbances than to the internal PD originated sound waves. They are also affected by distortion within the tank from the winding, core and support structures in the transit path which influences can partly be eliminated with appropriate signal processing afterwards. The compromise is therefore, to use a combination of the two methods, using sensitive UHF signals to provide trigger signals and by using averaging [5] of acoustic signals for de-noising.

2 FUNDAMENTALS OF UHF PD LOCATION

With transformers possessing two oil filling valves, PD location can be performed with two UHF probes, e.g. located opposite each other. The simplest possibility is that the PD is located in the middle of the transformer, in-between both probes, see Figure 2.

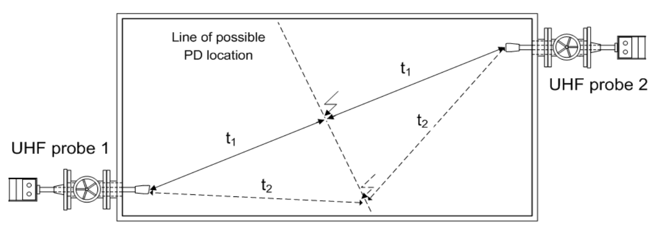

Figure 2. Geometrical PD location with two UHF probes in the case where the PD source is in the middle of the transformer.

The emitted waves travel to both probes and result in the same travel time of t_1. The measurable propagation time difference t_m between both probes is zero. The location result is not unique because, as shown with the dotted PD source in Figure 2, there are other possible PD locations causing a measurable propagation time difference of t_m=0. Signal propagation time to both probes is here t_2. Possible PD locations causing that measurement result are located along the dotted line normal to the line between both probes. With that location accuracy, not more than the PD affected phase limb can be located without any further measurement. For more precise location, further acoustic measurements can be undertaken with that starting information regarding a promising measuring area around the transformer.

In case where the PD source is located somewhere other than the middle position within the transformer, a propagation time difference t_m can be measured between the signals of both probes. That propagation time difference results in a sphere around probe 2, see dotted sphere correlating to that propagation time difference in Figure 3.

In the case that the PD is located on the direct line between both probes, the PD is located centrally between the sphere and probe 1. Then it is causing the travel time t_a to the first probe and to the sphere, and the resulting propagation time difference of t_m is measurable. Again that location is not unique because the PD can also be located as shown in Figure 3 on the dotted line. That PD source will cause the same measurable propagation time difference of t_m with the same non-measurable travel time of t_b to probe 1 and in the direction of probe 2.

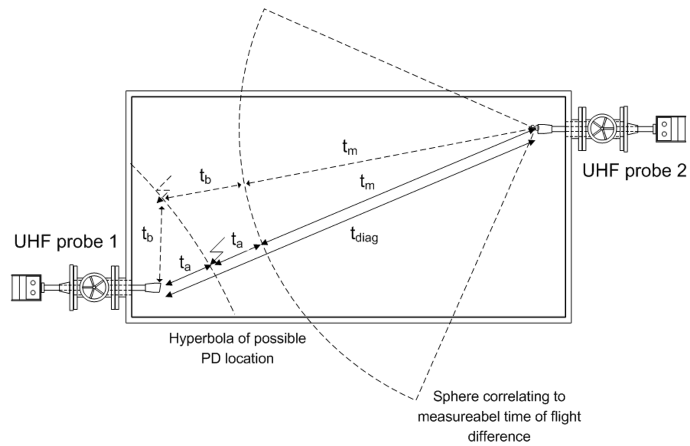

Figure 3. Geometrical PD location with two UHF probes in the case where the PD source is somewhere in the transformer.

The dotted line of possible PD locations is defined by points of the same distance between the sphere and probe 1, which is the mathematical definition of a hyperbola as shown in Figure 3. Regarding the dimensions of power transformers the hyperbola can be approximated by a line or an area inside the transformer. The error between the hyperbola and the line increases with an increasing distance to the diagonal line between the measuring probes. That means the spatial deviation between the hyperbola and the approximated area is the greatest at the tank wall. But normally that error between hyperbola and approximated area can be neglected because possible PD sources are located at the active part centred in the tank.

The area of the possible PD location is defined by the distance D between the PD source and the respective probe. That distance D can be determined by multiplying the time t_a with the speed v_{oil} of UHF waves in oil:

$$D = t_a \cdot v_{oil} \qquad (1)$$

The speed of UHF waves in oil v_{oil} can here be calculated by the speed of light in vacuum divided by the square root of the relative permittivity ε_r = 2.2 of mineral oil:

$$v_{oil} = \frac{c_0}{\sqrt{\varepsilon_r}} \approx 20cm/ns \qquad (2)$$

The propagation time t_a and can be calculated by t_{diag} which is the propagation time between both probes diagonal through the transformer and the measurable propagation time difference t_m:

$$t_a = \frac{t_{diag} - t_m}{2} \quad (3)$$

The location accuracy is limited to an area with possible PD source locations inside the transformer. That might identify the phase limb and might save a lot of time for locating positions outside the tank where acoustic signals are measurable for more accurate location purposes.

The presented method is demonstrated with the help of the following case study.

3 PD LOCATION BY UHF PD MEASUREMENTS

On-site UHF PD measurements were made on a 45 year old generator step-up transformer with the rated voltage of 110/10 kV and the rated power of 120 MVA. Due to 8 years stand still time period, operational experience is missing. A condition assessment regarding PD activity before putting the unit back into service was performed with two UHF probes, see Figure 4.

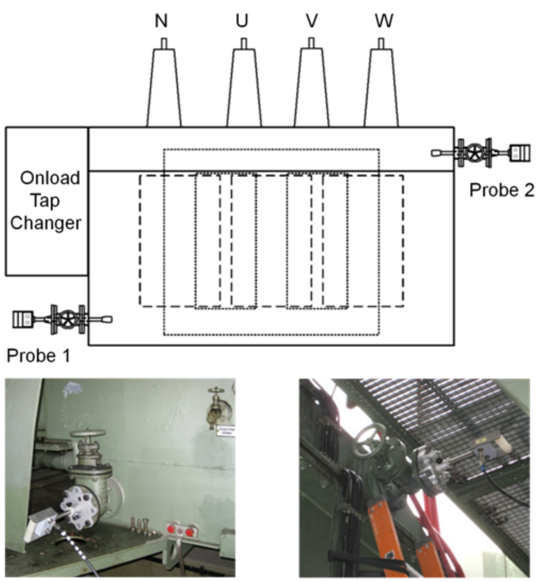

Figure 4. UHF probes installed at a 120 MVA generator step-up unit.

The transformer was disconnected from the grid (off-line) and energised using a three-phase PD free generator unit (110 kVA) to minimize the influence of external disturbances. The transformer was excited via the 10 kV windings.

3.1 UHF MEASUREMENTS

The transformer possesses two oil filling valves, see Figure 4. The first valve is underneath the tap changer housing at the height of the lower core. The second valve is on the opposite side at the top of the transformer. By means of artificial UHF impulses the so called Performance Check [7] was performed to demonstrate the sensitivity of the measuring system attached to the two UHF probes. Following measurements with transformer's excitation to nominal voltage revealed UHF signals at both UHF probes, see Figure 5. The unamplified signals are recorded with an oscilloscope with the analogue bandwidth of 3 GHz.

Both figures on the left hand side and on the right hand side show two time signals of one PD source. In Figure 5 a), probe one measured the UHF signals first, and with a higher amplitude than probe two. Hence it could be stated that the located PD source is closer to probe one.

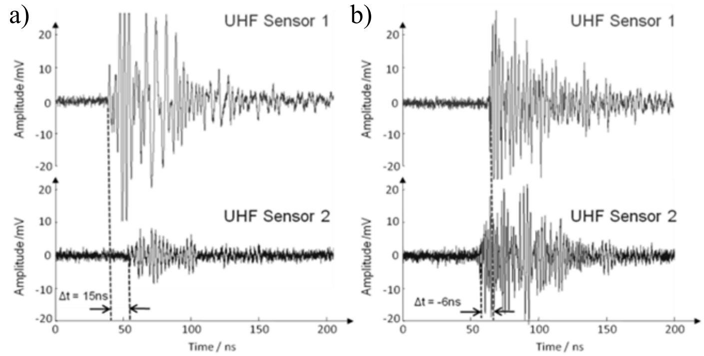

Figure 5. Measured propagation time differences with two different sensors for source 1 (a) and source 2 (b).

In Figure 5 b), the amplitudes of both probes are almost the same and the signals have just a small propagation time difference. According to that it is assumed that the PD source emitting these signals is in the middle of the transformer, because of the same distances and propagation time between the probes. In a time interval of 30 seconds about 100 impulse signals of both UHF PD probes were recorded by the oscilloscope. The PD pulse repetition rate was much higher but limitation was the storage speed of the oscilloscope.

In order to locate the PD, the propagation time difference of both UHF signal has to be determined. In order to have an automated analysis for the 200 signals, here the propagation time is determined by a simple signal amplitude threshold value above the noise level. This definition of the beginning of a signal is quite inaccurate; however it is sufficient for a first impression. With the starting point of the UHF signals the propagation time difference t_m can be distinguished and with equations (1), (2) and (3) the distance D between the PD source and the respective probe is calculated.

The resulting distance D is related to the probe which was reached first by the UHF waves. For simplifying the visualisation of the distances they are related to the middle of the line between both probes. A positive value means that the PD defect is closer to probe 1, a negative value means that the PD defect is closer to probe 2. With that information it is possible to identify the limb, where the PDs occur. A statistic analysis of the resulting PD locations of about 100 signals, each recorded at both probes, is shown in Figure 6.

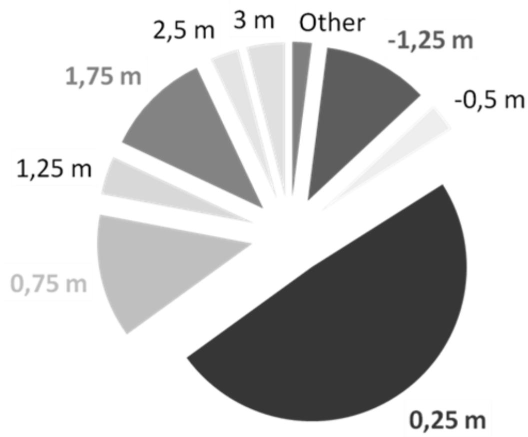

Figure 6. Spatial deviation from middle position of PD.

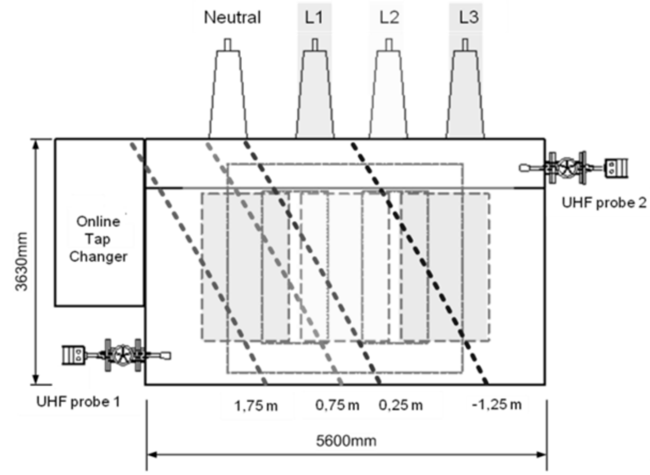

Figure 7. Dotted lines as planes inside the transformer representig the spatial distribution of PD activity in the transformer.

The measurement tolerance of these data amounts to ±30 cm (±1.5 ns). Those PD events that occurred only once are summarised under "Other". The size of the pieces of the pie chart represents the amount of pairs of UHF signals resulting in that specific location. E.g. the biggest piece is representing 47 pairs of UHF signals indicating a PD 0.25 m from middle position.

According to IEC 60270 measurements, that were performed simultaneously [6], four different PD sources are active inside the transformer. That is confirmed by the measured UHF signals and four main clusters in Figure 6. They represent approx. 80% of the received signals. The cluster "0.25 m" is recognizable as the most active PD source with approx. 50% of all measured signals. The source is almost in middle position within the transformer with 0.25 meters in direction of probe one.

In Figure 6 there are additional clusters recognizable representing approx. 20% of the received signals. Those measured propagation time differences might be explained by the possibility of additional active PD sources. Also a wrong determination of the propagation times can cause such a measuring result, because it bases on the fact that electromagnetic waves propagate straight through the transformer tank. In fact, propagation is to some unknown extent influenced by the inner mechanical structure – mainly the active part – of the transformer. UHF signals can't pass the iron core and have to travel around it. By that the measurable propagation time is increased. Furthermore UHF signals of one and the same PD source can reach the probes by different paths and account for different measurable propagation time differences. Thus the calculated PD origins underlie certain inaccuracies.

Figure 7 shows lines as possible PD origins for the four main clusters of Figure 6. The lines are calculated on the base of signal propagation time differences of Sensor one and Sensor two and determine where possible PD locations inside the transformer tank can cause the corresponding propagation time difference. The line of the cluster "0.25 m" is located nearly in the middle between both probes and is represented by the corresponding line.

Assuming the dimensions of the active part like plotted in Figure 7 and knowing by the simultaneous IEC 60270 measurements [6] that there must be a PD source in phase L2, the line of possible PD sources crosses the active part at middle height and bottom of phase L2. In case, transformers have only one PD source, that source would have been located and additionally acoustic location might start searching at the corresponding area for further proof.

Here the transformer has more than one PD source. The four most frequently appearing propagation time differences are plotted in Figure 7. For cluster "-1.25 m" the location can only be estimated to be in phase L3, whereas cluster "1.75 m" leads more precise to the bottom of phase L1. Cluster "0.75 m" is a second PD source somewhere at the top of phase L_1.

Concluding, propagation time differences are measurable in UHF frequency range. For precise location, at least four UHF sensors are needed, although rough estimation of PD location is in some cases possible with only two sensors. Unfortunately, transformers don't have more than three oil filling valves normally. Therefore acoustic measurements will still be needed in future.

3.2 ACOUSTIC MEASUREMENTS

Because of runtime information of the two UHF sensors and due to the availability of a sensitive trigger event for PD by UHF signals, an acoustic measurement was performed. The measurements according IEC 60270 and the propagation time information of the UHF signals allowed a rough location of the PD sources. Due to that rough location the acoustic sensors were installed at corresponding locations at the transformer tank, but no acoustic signals were detectable. Due to the fact, that more than one PD source is active in the transformer the de-noising method of averaging acoustic signals with UHF trigger (described in next chapter of this contribution) was not applicable, because of possibly interfering acoustic signals of different sources which didn't overlay constructively.

3.3 SUBSEQUENT ACTIONS

Due to the measurable PD activity the unit was put back into service with online PD monitoring equipment for ongoing research [8].

4 PD LOCATION WITH COMBINED UHF AND ACOUSTIC MEASUREMENTS

Because of increasing gas-in-oil values, a 333 MVA, 400/220kV single-phase autotransformer was tested on-site and on-line for PD. The high noise level at site strongly disturbed the conventional PD measurements made according to IEC 60270 at frequencies lower than 1 MHz. Source of noise was in that case the 400 kV bus bar above the transformer producing audible corona discharge. Consequently, UHF PD measurements for PD detection in combination with acoustic measurements for PD location were performed in order to get reliable results [11].

4.1 UHF MEASUREMENTS

In this case the transformer possessed three oil filling valves and three identical UHF Sensors were installed. Figure 8 shows the positions of the UHF sensors (UHF 1 – UHF 3). Two sensors are opposite to each other at the top of both front ends of the tank and the third (UHF 3) is located at the bottom in the middle of the transformer side, see Figure 8.

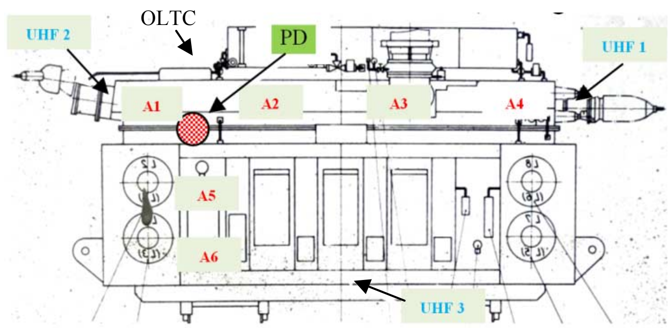

Figure 8. Positions of UHF Sensors, acoustic sensors in the same plane and the PD source at 333 MVA single phase autotransformer

First, the so called dual port Performance Check was done [7]. Artificial UHF impulses were injected at each sensor with a signal generator (60 V at 50 Ω). It was not possible to detect the artificial impulses at any combination of emitting and receiving sensor. Manufacturers design drafts explains this strong damping of the UHF signals by tubes installed behind the oil filling valves in order to direct the oil flow around the winding. According to the unsuccessful dual port Performance Check it could be stated, that the sensors are electromagnetically decoupled from each other and might also be shielded against UHF pulses from internal PDs.

A further explanation might be that the maximum signal generator output voltage of 60 V is not sufficient to transmit UHF waves through that transformer.

But nevertheless, at nominal voltage, UHF signals from internal sources were detectable with all three sensors. I.e. the internal PD causes UHF signals with higher energy content than the applied artificial impulses. It can be concluded that the Dual Port Performance Check is thus just a worst-case estimation of the sensitivity. But even though the Performance Check is not successful, sensitive UHF measurements might still be possible.

Frequency analysis of the measured signals of the installed UHF probes proved the shielding characteristic of the tank, see Figure 9. The signals features frequency contents of up to 1 GHz, as emitted by a broadband emitter of UHF waves, like internal PD in oil. External disturbing sources would have been narrow banded, e.g. at around 500 MHz for digital video broadcasting or around 900 MHz or 1800 MHz for GSM since there are often modulated carriers. In Figure 9 the unamplified measured signals of the UHF probes are shown with their frequency analyses (FFT).

Propagation time differences in the range of nanoseconds (ns) are recognisable between the signals. Taking propagation time differences caused by different lengths of measuring lines into account, a first estimation of the geometric PD location pointed to the on-load tap changer (OLTC) on the left hand side of the transformer. That is supported by the measured UHF amplitudes of the three UHF probes. The probe nearest to the tap changer (probe UHF 2) has the highest reading output of 10 mV, whereas the other probes did not reach more than 5 mV. Therefore probe UHF 2 was used for triggering and determining the starting time in order to calculate the propagation time differences.

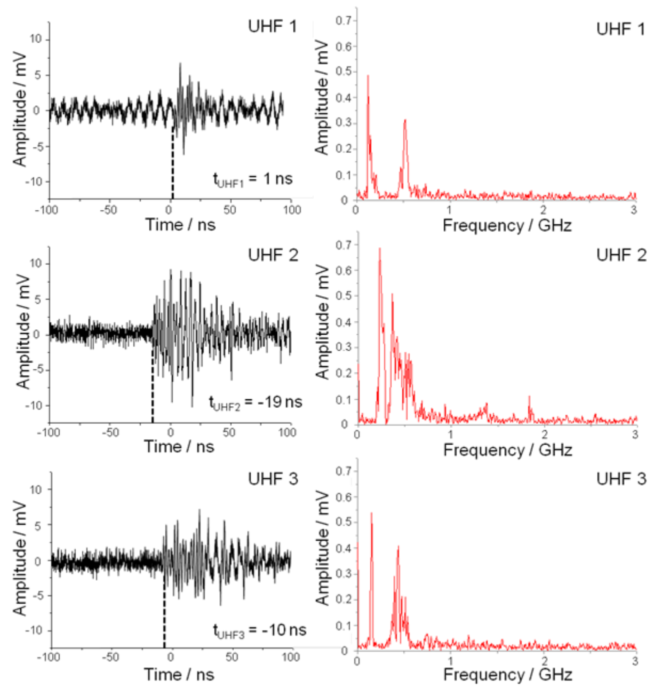

Figure 9. Measured propagation time differences between three UHF probes at different locations (unamplified signals) and frequency spectrum of signals to prove broadband emission.

4.2 ACOUSTIC MEASUREMENTS

PD also produces acoustic waves, which are measured with piezo-electric sensors installed at the outer tank wall. Their measurable frequency range is between 50 and 200 kHz. Due to comparatively high acoustic signal attenuation within the solid and liquid insulation material and structures inside the transformer sensitive acoustic measurements are hard to achieve [9]. Additionally acoustic signals of PD might be covered by ambient mechanical noise and inherent noises within the transformer (core noise). Summarising, exclusive acoustic PD measurement is only useful to a limited extent. To increase the sensitivity of acoustic measurements the method is combined with the more sensitive UHF measuring method. UHF signals are used as trigger signals in order to activate the acoustic measurement during the occurrence of UHF PD signals. By using averaged signals (averaging in time domain), the acoustic PD pulses remain constructively overlapped whereas the white background noise is averaged to zero. Thus the signal to noise ratio of the acoustic signals is increased.

The UHF measuring method is based on electromagnetic waves, which spread with approximately two-thirds of speed of light inside the transformer. Thus for location, UHF signals are detected almost the same time PDs occur enabling the use of UHF signals as a trigger for acoustic measurements. Conversely, the speed of acoustic waves is 1400 m/s [10], producing transit times within the range of milliseconds. Geometrical distances between sensors and the source of PD (calculated from the propagation times of the individual acoustic sensors) result in a spherical area inside the transformer. With at least three acoustic sensors and corresponding propagation times, it is possible to calculate the intersection of the spheres and thus to determine the PD location. It must be assumed that the acoustic waves travel directly in the line of sight from the PD source through the oil and through the steel tank to the sensor without any reflections. But furthermore the location process has also to deal with acoustic waves travelling faster through the tank wall than through the oil. The propagation times of the acoustic signals can be computed objectively with the help of the Hinkley criterion [5 pp. 82 ff],[9]. It is based on the signal energy of the measured signal and results in an absolute minimum for the signal starting point.

Figure 8 depicts the positions of the used acoustic sensors (A1 – A6). As an example Figure 10 shows the measured and averaged acoustic signals of the acoustic sensors A5 and A6. Averaging was performed with approx. 100 signals. Although averaging was used the signal to noise ratio is quiet low, thus the determination of the propagation times was only possible by application of the Hinkley criteria. The respective propagation times are t_{A5} = 1.03 ms and t_{A6} = 2.07 ms.

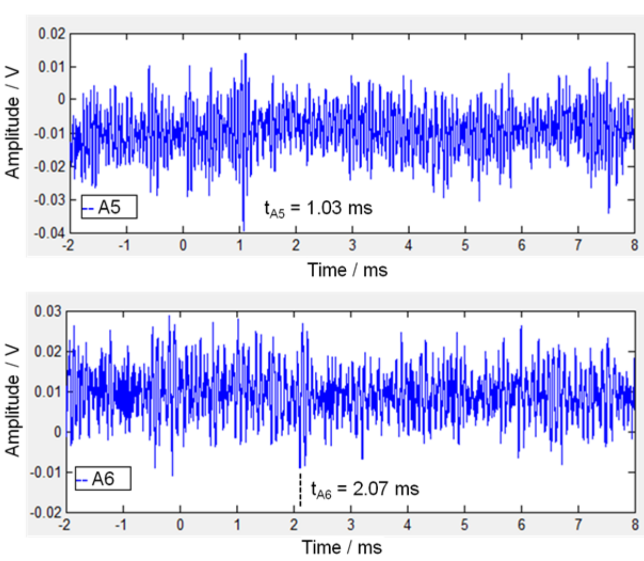

Figure 10 Example of averaged acoustic signals with determinated propagation time measured at 333 MVA transformer.

Based on the determined propagation times the supposed position of the PD source is located in the vicinity of the tap changer (Figure 8). Geometrical inaccuracy is within the range of approx. 40 cm on all space axes. This inaccuracy is caused by using different combinations of propagation time differences and different location methods [5].

4.2 REPAIR

After transportation of the transformer to a factory the location result was confirmed by an IEC triggered acoustic measurement in test area and the transformer was detanked for inspection and repair.

The visual inspection of the tap leads at the tap changer region confirmed the location results and revealed deteriorated paper insulation, see Figure 11.

Figure 11 Deteriorated paper insulation on leads at the tap changer.

After repair of the affected leads the transformer passed the acceptance test without any indication of PD activity and was put back into service.

5 CONCLUSION

Propagation times measured in the UHF range can be used for geometrical PD location within power transformers. Additionally, different measurable UHF amplitudes allow an estimation of the PD location. The accuracy with, e.g., two UHF sensors is adequate to determine the phase where the PD is located, or whether the PD source is near the tap changer. However, since transformers rarely offer more than three UHF oil valves, an additional acoustic measurement method is usually required for location. Using the knowledge gained from the UHF measurement, acoustic sensors can be placed near the PD source at the transformer tank to speed up the location process.

Acoustic sensors have to be placed near to the PD source at the transformer tank in order to achieve acoustic signals of the PD. However, acoustic sensors are normally more sensitive to external disturbances like mechanical noise than to internal

PD originated sound waves, because internal sound waves experience a relatively high attenuation on their travelling path to the sensor. They are also affected by distortion within the tank from the winding, core and support structures in the transit path. Those influences can later be eliminated with appropriate signal processing. Therefore, the optimal solution is a combination of methods, e.g. using sensitive low-frequency electric or UHF PD signals to provide triggering and by using averaging of acoustic signals for de-noising. In the case of more than one PD source, acoustic location can become difficult because of interfering signals.

To achieve an objective propagation time determination the use of automatically working algorithm e.g. using the Hinkley criteria is helpful and often necessary.

A successful PD source location on-site strongly supports the decision about the subsequent actions like scrapping or repairing.

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Sebastian Coenen received the Dipl.- Ing. degree in electrical engineering in 2005 from the Technical University of Aachen, Germany. In 2012 he received the Dr.-Ing. degree from the University of Stuttgart, Germany, for his work as scientific assistant at the Institute of Power Transmission and High Voltage Technology. His main research topic was in the field of the ultra high frequency partial discharge detection in power transformers and the localization of partial discharges with combined ultra high frequency and acoustic partial discharge measuring methods.
At present, he is working for Siemens AG, Transformer Lifecycle Management (TLM) in Nürnberg within the R&D department as project manager. Dr.-Ing. Coenen published over 25 papers and is member of CIGRE and VDE-ETG.

Stefan Tenbohlen received the Diploma and Dr.-Ing. degrees from the Technical University of Aachen, Germany, in 1992 and 1997, respectively.
In 1997 he joined ALSTOM Schorch Transformatoren GmbH, Mönchengladbach, Germany, where he was responsible for basic research and product development and in this function working in the field of on-line monitoring of power transformers. From 2002 to 2004 he was the head of the electrical and mechanical design department. In 2004 he was appointed to a professorship and head of the institute of Power Transmission and High Voltage Technology of the University of Stuttgart, Germany. In this position his main research fields are diagnostic of equipment of power transmission, development of high voltage measurement technique, behavior of gas insulated insulation systems and different aspects of electromagnetic compatibility (EMC). Prof. Tenbohlen holds several patents and published more than 250 papers. He is member of the IEEE, CIGRE and VDE ETG. He is convener of CIGRE WG A2.37 (Transformer Reliability Survey) and member of CIGRE A2 (Power Transformers), and several other international working groups.