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On-site Experiences with Multi-Terminal IEC PD Measurements, UHF PD Measurements and Acoustic PD Localisation

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***Abstract*— The paper presents the experience using a combination of different partial discharge (PD) measurement methods both to detect PD in power transformers and to improve interpretation and localisation of their sources.**

The multi-terminal PD measurement is illustrated here using STAR diagrams for discrimination between external noise clusters and multiple internal PD sources. Several different PD sources in different phase windings during an off-line measurement on a power transformer were detected and the UHF method confirmed these results and conclusion.

The UHF PD measurement method is usable as stand-alone measurement and as a supporting measurement for off- and on-line PD detection. Fundamental knowledge of the PD phenomena is needed for interpretation of measuring results, comparable to knowledge of the lower frequency IEC 60270 measurements. UHF sensors are easily installable and useable. The sensitivity of UHF PD measurements is sufficient and normally is 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 localisation of PD. UHF oil filling valves are often electro magnetically shielded from the internal tank by tubes for directing the oil flow. But sensitive UHF measurements are still possible, and additionally broadband amplifiers can be used to improve detection sensitivity to UHF signals.

Time of flights measured in the UHF range can be used for geometrical PD localisation. The accuracy seems to be adequate to determine the phase where the PD is located. Additionally, different measurable UHF amplitudes support an estimation of the PD location. However, since transformers rarely offer more than three UHF oil valves, an additional acoustic measurement method is usually required for localisation. Using the knowledge gained from the UHF sensors, acoustic sensors can be placed near to the PD source at the transformer tank. During an on-line measurement a PD source localisation was performed with the help of measured UHF time of flights and acoustic time of flights.

KEYWORDS: Power Transformer – Partial Discharges – On-site PD measurement - IEC 60270 – UHF-method - Acoustic PD Localization – Multi-Terminal PD Measurement

I. INTRODUCTION

The reliability of electrical energy networks depends on the quality and availability of primary electrical equipment such as the power transformer. Localised internal insulation failures can, however, lead to catastrophic breakdowns and incur long outage and penalty costs. To reduce such risks it is normal for power transformers to have passed a range of factory tests including one for partial discharge (PD) activity before acceptance and commissioning. Once installed it is costly to energise with e.g. induced test voltage or resonant sets. Additionally the results are often restricted by high site interference. Many users then rely on integrated detection methods such the use of dissolved gases in the oils. However, this need not be the case. The UHF, acoustic and multi-terminal PD measurement methods are using different physical peculiarities of the PD phenomenon, e.g. electric currents according to IEC 60270 [1], electromagnetic waves (UHF-range) and acoustic radiation.

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. Due to the existing coupling of the three phases in a transformer, single partial discharge pulses in one certain phase can also be measured as cross coupling signals in all phases. Evaluation of multi-terminal PD measurements establishes an approach to clearly distinguish between multiple PD sources and to remove external disturbances [2].

The so called "UHF PD measuring method" (UHF: Ultra High Frequency) 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). Due to the moderately attenuated propagation of UHF waves inside the transformer tank, the sensitivity to electromagnetic wave detection is good [3]. UHF sensors [4] can be inserted into the transformer during full operation through the oil filling valve. 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.

When electrical or UHF PD measurements confirm PD activity, a three dimensional localisation of PD sources is the

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next step for risk evaluation of PD phenomena. With three space coordinates and a time dimension relating to a single PD event, the number of unknowns' requires four sensors for arrival time measurements and location. UHF technology offers this possibility but access for most designs is normally limited to 3 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 localization 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 triggering and by using averaging [5] of acoustic signals for de-noising.

II. *Comparison of Multi-Terminal PD Measurement and UHF PD Measurement*

On-site multi-terminal electric and UHF PD measurements were made on a generator step- up transformer 110/10 kV, 120 MVA, see Figure 1. This on-site measurement was performed with the transformer off-line and energised using a three-phase PD free generator unit (110 kVA) to minimize the influence of the external disturbances. The transformer was excited via the 10 kV windings.

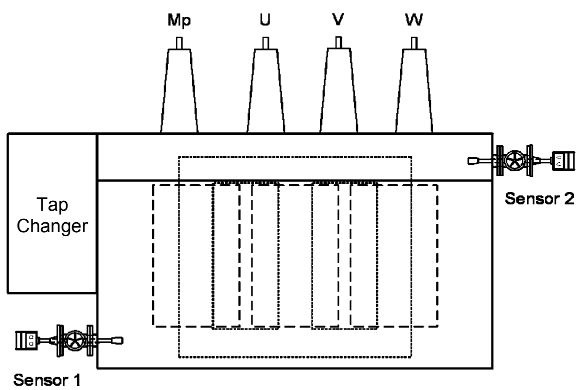

Figure 1. UHF sensors at a 120 MVA generator step-up transformer

A. *Multi-terminal PD measurement*

The calibration of the measurement arrangement in terms of apparent charge was done separately for all three measurement devices with a defined calibrator impulse. The multi-terminal measurements were performed with PD Smart from Doble Lemke and mpd540 from Omicron [7]. Results of the measurements at the 110 kV side are shown in Figure 2. On the left hand side the upper diagrams show the PRPD pattern of phase L_1 (left) and L_2 (right) and the lower diagrams present the PRPD of phase L_3 (left) and the neutral triggered on phase L_1 (right). The rectangles show the PD in L_1 and the respective coupling on phase L_2 and L_3.

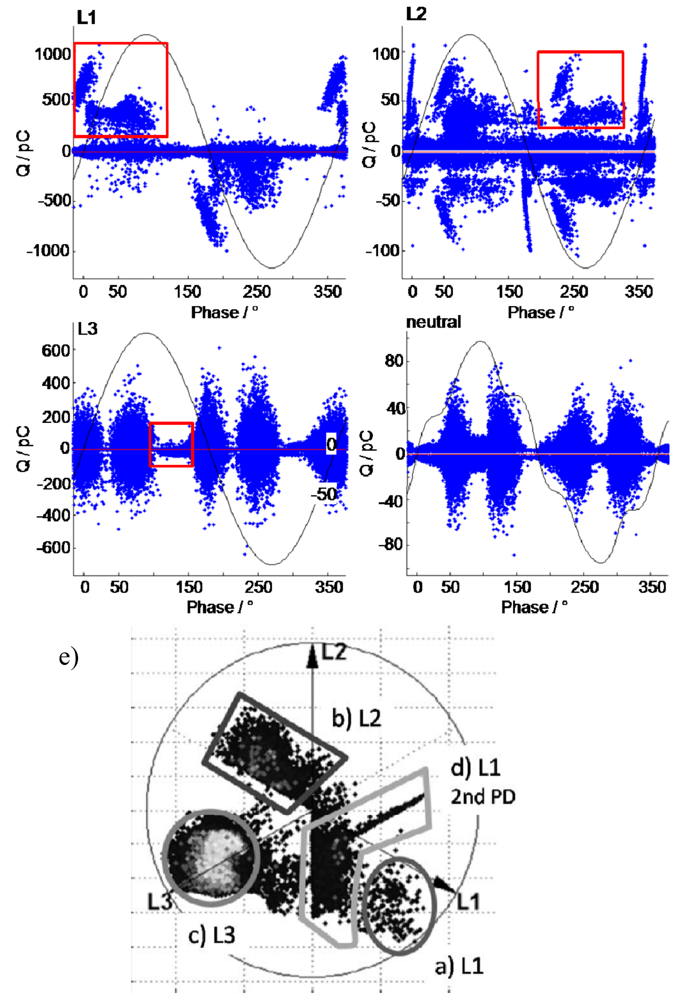

Figure 2. PRPD pattern of the transformer on phase L_1, L_2, L_3 and neutral; a) L1, b) L2, c) L3, d) L1-2nd, e) STAR-diagram with four clusters

The measurement on the neutral is a good method for comparing the UHF PRPD pattern (see Figure 5) with the conventional PD pattern because all internal PDs are visible in this pattern. The STAR diagram is a two-dimensional plot with a 120° phase shift of the three phase axis. If the signal of a PD can be measured on all phases because of cross-talk of the windings, an addition of the signal amplitude vectors of the three phases builds a point in the STAR diagram [7]. By means of the STAR-diagram, see Figure 2 (bottom), four different PD sources can be distinguished, one in phase L_2, one in phase L_3 and two in phase L_1.

The reverse transformations of each cluster in the STAR diagram confirm the four PD sources. Figure 3 shows the patterns of the reverse transformed clusters of the PD sources in L_1 (a), L_2 (b) and L_3 (c). The pattern of phase L_2 could be a void in oil. The PD source of L_1 with the maximum of 1000 pC was the highest detectable value and occurred after some minutes during the measurement also showing characteristics of void PD pattern. The PD source in L_3 was the first occurring signal at 40 kV. The level of the PD increased with increasing voltage showing cross-coupling from PDs of other phases.

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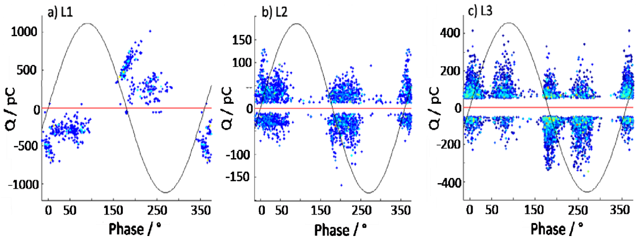

Figure 3. PRPD pattern of the generator step-up transformer after retransformation of clusters in the STAR-diagram: a) L1, b) L2 and c) L3

B. UHF Measurements

By means of artificial UHF impulses the so called Performance Check was performed to demonstrate the workability of the measuring system shown in Fig. 1 [6]. Following measurements with excitation revealed UHF signals at UHF sensors, see Figure 4.

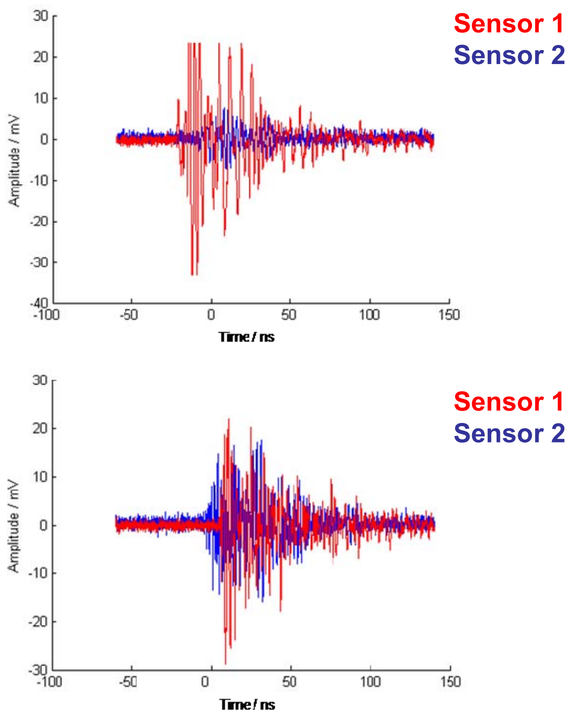

Figure 4. Measured time of flight differences with two different sensors for source 1 (top) and source 2 (bottom)

The red signals were recorded with sensor 1 below the tap changer; the blue signals were recorded with sensor 2 on the opposite side. Both figures show two time signals of different PD sources. In Figure 4 (top), sensor 1 measured the UHF signals first and additionally with higher amplitude than sensor 2. Hence it could be stated, that PD source 1 is nearer to sensor 1. In Figure 4 (bottom) the amplitudes of both sensors are nearly the same and the signals have just a small time of flight difference. According to that it is assumed, that PD source 2 is in the middle of the transformer because of same distances and time of flights between the sensors. With that information it is possible to identify the limb, where the PDs occur. Evaluation of approx. 100 time signals confirmed that there are four active PD sources inside the transformer [7]. Phase identification with the UHF PD Measurements can be confirmed with the four clusters of PD within the STAR-diagram. The measured UHF PD events of UHF-sensor 1 were synchronised to the phase L1 of the AC test voltage and stored for a period of three minutes as seen in Figure 5.

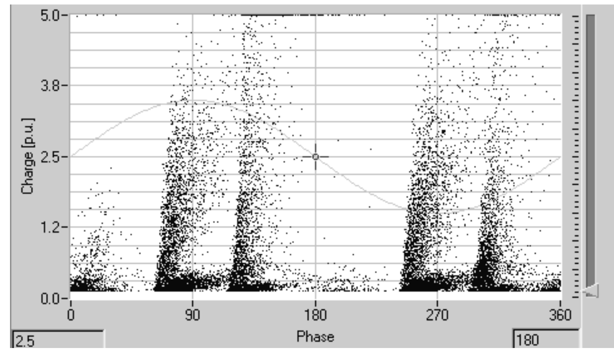

Figure 5. UHF PRPD-pattern of 120 MVA Generator Step-up Transformer – 500-510 MHz, 35dB amplificaton, 3 min, synchronised to phase L1

The resulting PD pattern shows overlapping patterns of PDs activity on different phases. The comparison of the UHF PD data with IEC conform measured data reveals comparable patterns as seen in Figure 2c.

C. 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 IEC measurements and the arrival time information of the UHF signals allowed a rough localisation of the PD sources. Due to that rough localisation the acoustic sensors were installed at corresponding locations at the transformer tank, but no single 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.

III. PD Localisation with Combined UHF and Acoustic Measurements on Grid Connected 333 MVA Transformer

Because of increasing gas-in-oil values, a 333 MVA grid coupled 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. Consequently, UHF PD measurements for PD detection in combination with acoustic measurements for PD localisation were performed in order to get reliable results.

By means of several PD decoupling ports for IEC 60270

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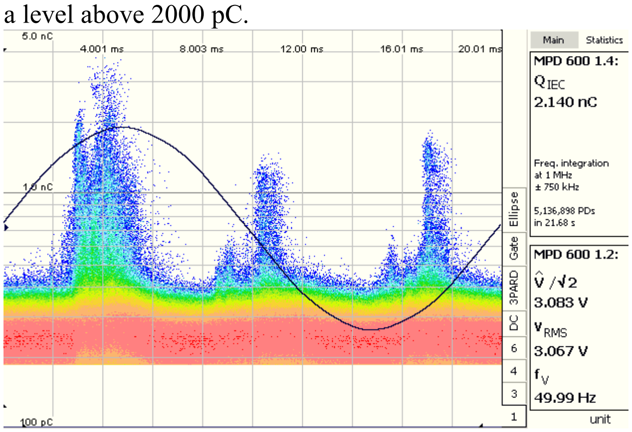
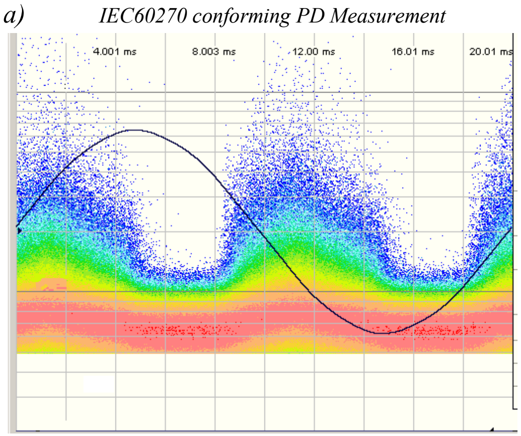
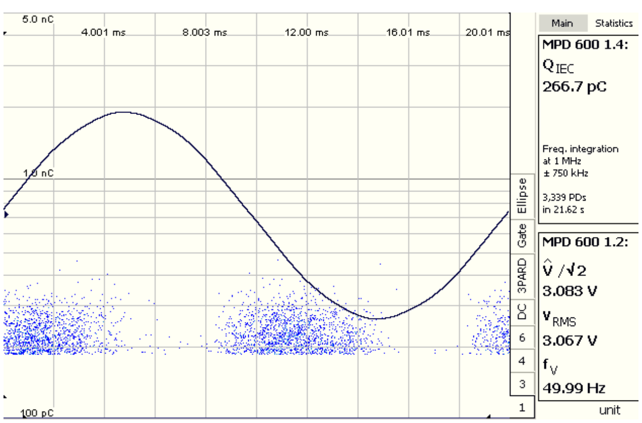
measurements a multi-terminal PD measurement was performed. Thus external disturbances like corona should be measured on all terminals with similar pulse shape and amplitude and it should be possible to distinguish between multiple PD sources and external noise by means of the respective STAR diagram [7]. But in this case the 400 kV bus bar above the transformer disturbed the multi-terminal measurement so much that the STAR diagram delivered no usable results. A lower frequency IEC 60270 measured PRPD-pattern is shown in Figure 6 (a). The external disturbing corona discharges with the phase shift of 120° of the three different phases become visible in the pattern with a level above 2000 pC.



a) IEC60270 conforming PD Measurement



b) UHF PD Measurement at 310 MHz



c) Gating of IEC measurements by UHF signals

Figure 6. Gating of IEC measurements by UHF signals

Internal UHF sensors uses the tank wall as shielding against external disturbances and Figure 6 (b) shows the pattern of one internal UHF sensor. According to this pattern only one internal PD source can be identified by phase stable UHF pulses. The 120° shifted disturbances are no longer detected. Using the UHF signals of internal PDs as a trigger or in other words gating signal for the IEC method, the PD measurement leads to the pattern of Figure 6 (c). The combination technique is called “Gating” or “Windowing” [5] and allows an estimation of the apparent charge of only the internal PD in case of heavy external disturbances. For the internal PD the apparent charge might be estimated to be at about 300 pC. Compared to Figure 6 (a) with disturbances of around 2000 pC the sensitivity of IEC measurements is improved significantly by means of the UHF signal.

In this case the transformer possessed three oil filling valves and three identical UHF Sensors were installed. Figure 7 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 7.

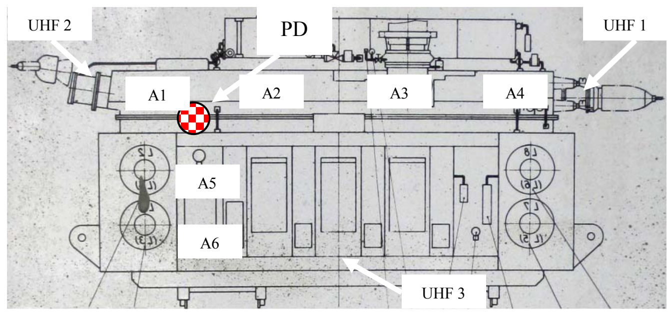


Figure 7. Positions of UHF Sensors, acoustic sensors and the PD source at 333 MVA single phase autotransformer

First, the so called dual port Performance Check was done. 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. This strong damping of the signals can be explained 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.

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.

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 measurement are sometimes hard to achieve [8]. Additionally acoustic signals of PD might be covered by ambient mechanical noise and

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inherent noises within the transformer (core noise). Summarising, exclusive acoustic PD measurement or on-line monitoring 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. Figure 7 shows the positions of the used acoustic sensors (A1 – A6).

The UHF measuring method is based on electromagnetic waves, which spread with approximately two-thirds of speed of light inside the transformer. Thus for localisation, UHF signals are detected almost the same time PDs occur. Conversely, the speed of acoustic waves is 1400 m/s, producing transit times within the range of milliseconds. Geometrical distances between sensors and the source of PD (calculated from the time of flights of the individual acoustic sensors) result in a spherical area inside the transformer. With at least three acoustic sensors and corresponding time of flights, 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 steal tank to the sensor without any reflections. But furthermore the localization process has also to deal with acoustic waves travelling faster in the tank wall than in the oil. The time of flights of the acoustic signals can be computed objectively with the help of the Hinkley criterion [5, 8]. It is based on the signal energy of the measured signal and results in an absolute minimum for the signal starting point.

As illustrated in Figure 7, the supposed position of the PD source is in the vicinity of the tap changer. Geometrical inaccuracy is thereby within the range of approx. 40 cm on all space axes. This inaccuracy is caused by using different combinations of time of flight differences and different localisation methods [5]. The different time of flight differences was measured with six different sensors which are the three UHF Sensors (UHF 1 – UHF 3) and the three acoustic sensors placed near to the PD source (A2, A5, A6).

After transportation of the transformer to the manufacturer the localisation result was confirmed by an IEC triggered acoustic measurement in test area and the transformer was detanked for repair. The visual inspection of the active parts at the tap changer confirmed the localisation results.

IV. Conclusion

The multi-terminal PD measurement can be advantageously used by means of STAR diagrams for discrimination between external noise clusters and internal PD sources. Different PD sources at different phases were found and the UHF method confirmed the results of multiple PD sources inside the transformer. Nevertheless overlaying strong noise might make this method unusable.

The UHF PD measurement method is usable as stand-alone measurement and as supporting measurement for off- and on-line PD detection. Fundamental knowledge of the PD phenomena is needed for interpretation of measuring results, comparable to the knowledge needed for IEC 60270 measurements. UHF sensors are easy to install and use. The sensitivity of UHF PD measurements is sufficient and is normally not affected by external disturbances. So especially in noisy environments it is a very powerful and often superior method to support other PD measurement techniques. Oil filling valves used for the installation of UHF-sensors are often electro magnetically shielded from the internal tank by tubes for directing the oil flow. But sensitive UHF measurements are still possible and additionally, broadband amplifiers can be used to improve sensitivity of UHF detection.

Time of flights measured in the UHF range can be used for geometrical PD localisation. Additionally, different measurable UHF amplitudes allow an estimation of the PD location. With that knowledge, acoustic sensors can be placed near to the PD source on the transformer tank. Due to the fact, that normally no transformer offers more than three UHF oil valves, the acoustic measurement method is still attractive for PD localisation. In case of more than one PD source, acoustic localisation can become difficult because of interfering signals.

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