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Combination of Different Techniques for Improved Interpretation of PD Measurements

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SUMMARY

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 UHF PD measurement method is usable as single 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 probes 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 for measuring UHF signals sensitively.
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.
Run times 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 run times and acoustic run times.

KEYWORDS

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

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1 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 high 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, and 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 electromagnetic waves are detectable sensitively [3]. UHF probes [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 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 partly can 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.

2 CASE STUDY ON 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.

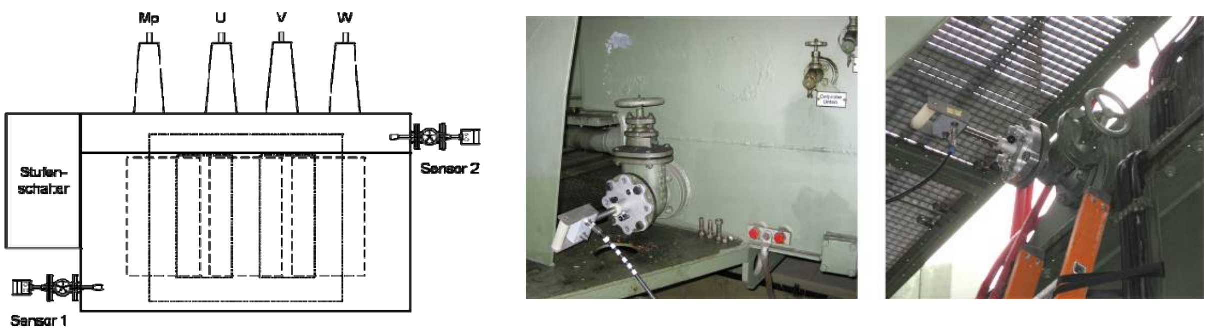


Figure 1: UHF probes installed at a 120 MVA generator step-up transformer

2.1 Multi-terminal PD measurement

The calibration of the measurement arrangement in terms of apparent charge was also 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. Results of the measurements at the 110 kV side are shown in Figure 2.

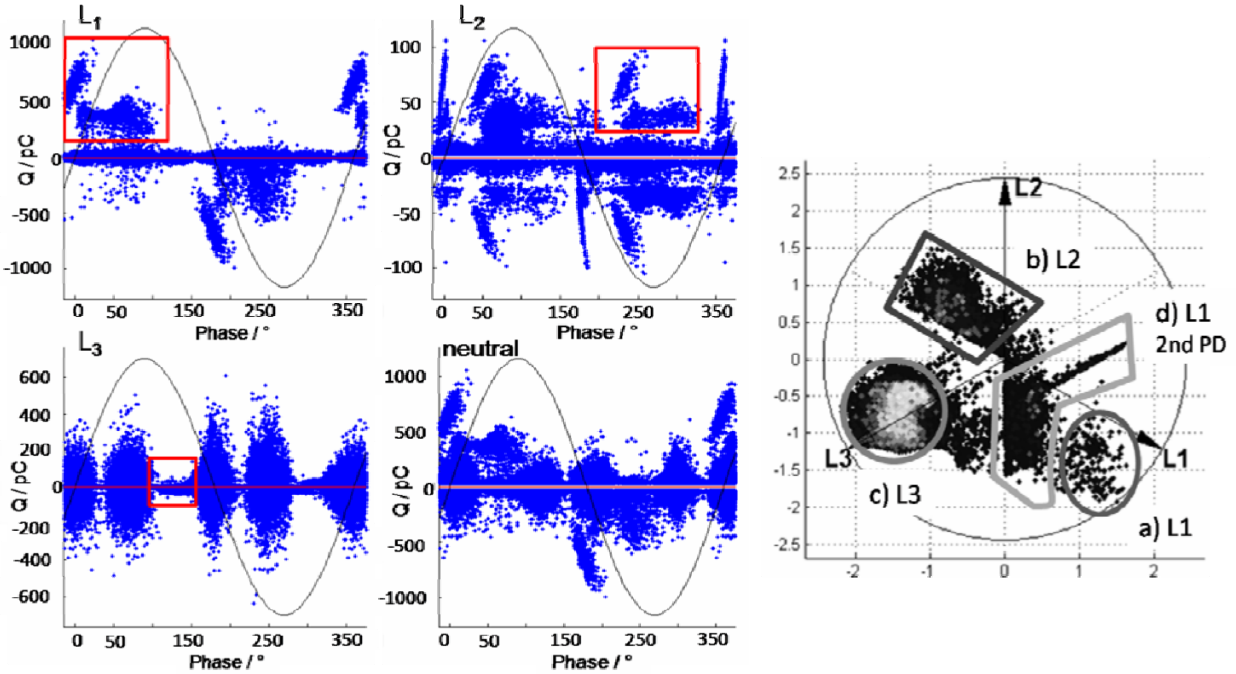


Figure 2: PRPD pattern of the transformer on phase L_1, L_2, L_3 and the neutral; STAR-diagram with four clusters: a) L1, b) L2, c) L3, d) L1-2nd PD

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 (right). The rectangles show the PD in L_1 and the respective coupling on phase L_2 and L_3. The measurement on the neutral is a good method for comparing the UHF PRPD pattern with the multi-terminal PD pattern because all internal PDs are shown in one diagram in different magnitudes. By means of the STAR-diagram, see Figure 2 (right), 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 confirm the four PD sources. The pictures in Figure 3 are the 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 PD of other phases.

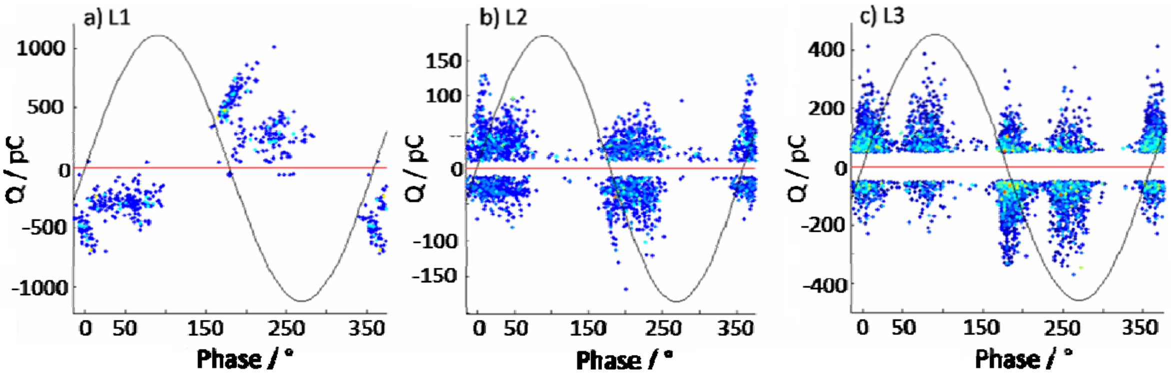


Figure 3: PRPD pattern of the unit generator transformer after retransformation of the cluster: a) L1, b) L2 and c) L3 in the STAR-diagram.

2.2 UHF PD measurement

The transformer possesses two oil filling valves, see Figure 1. The first valve is underneath the tap changer housing at the same height as the lower yoke. The second valve is on the opposite side underneath the oil expansion tank in the cover of the transformer.
The first measurement, a so-called dual port Performance Check [6], demonstrates the sensitivity of the measuring system. Wide-band signals of a signal generator were fed over the first UHF sensor into the transformer tank and measured with the second UHF sensor. Figure 4 represents the received time signal and its transformation in the frequency domain. During this measurement the transformer was not excited.

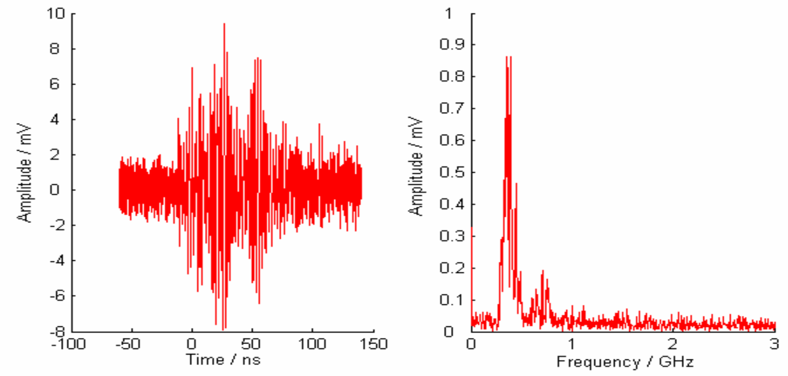


Figure 4: Dual port Performance Check

From the illustration it is evident that a wide-band signal (right, frequency portions up to 1 GHz) was travelling through the transformer and its active part. Likewise the signal-to-noise ratio is sufficient in the time signal (left). Therefore the sensors have been shown to be correctly installed and attached to the measuring instruments and a sensitive UHF measurement is possible. During the measurements with energisation UHF signals were measured with both probes. Run time differences allow a localisation of the PD source with additional analysis [7]. The measurable UHF PD events were synchronised to the phase L_3 of the AC test voltage and stored for a period of three minutes as seen in Figure 5.

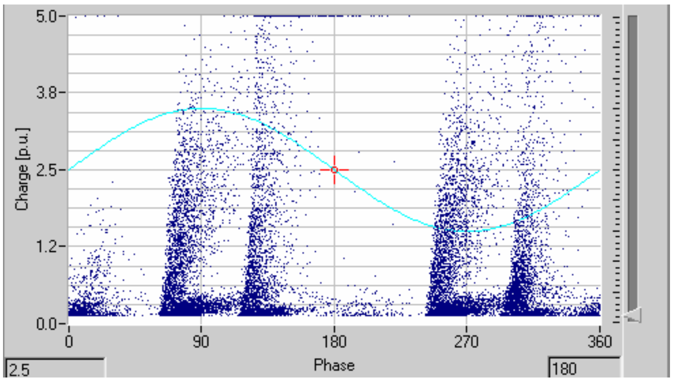


Figure 5: UHF PRPD-pattern of 120 MVA Generator Step-up Transformer – 3 min

The resulting pattern shows an overlap of the internal PD activity on the phases. The comparison of the UHF PD data with IEC conform measured data reveals comparable patterns as seen in Figure 2.

2.3 Acoustic Measurements

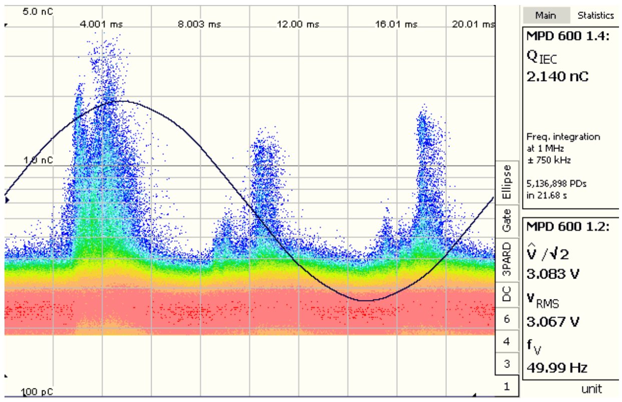
Because of runtime information of the two UHF sensors and due to the availability of a sensitive trigger event for PD by UHF signals, an acoustic measurement was performed. The IEC measurements and the arrival time information of the UHF signals allowed a rough localisation of the PD sources. Due to 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.

3 CASE STUDY ON PD LOCALIZATION WITH COMBINED UHF AND ACOUSTIC MEASUREMENTS ON GRID CONNECTED 333 MVA TRANSFORMER

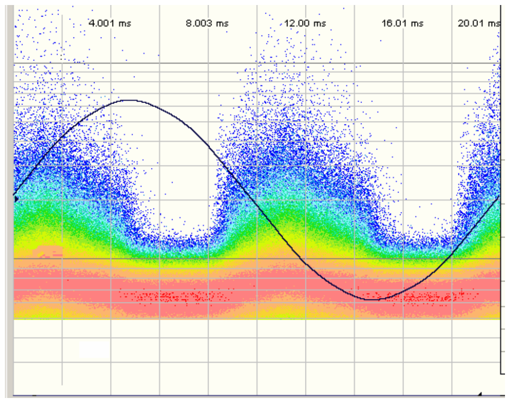
Because of increasing gas-in-oil values, a 333 MVA grid coupled single-phase autotransformer was tested on-site on-line for PD. The high noise level at site strongly disturbed the conventional PD measurements made according to IEC 60270 at sub 1 MHz frequencies. Consequently, UHF PD measurements for 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 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 feasible results.

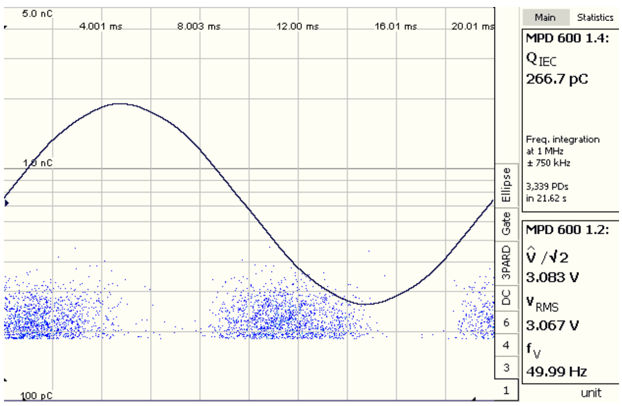
A lower frequency IEC 60270 measured PRPD-pattern is shown in Figure 6 (a). The external disturbing corona discharges with the phase shift of 120° of the three different phases become visible in the pattern with a level above 1 nC. Internal UHF probes uses the tank wall as shielding against external 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. The 120° shifted disturbances are no longer detected.



a) IEC60270 conforming PD Measurement



b) UHF PD Measurement at 310 MHz



c) Windowing or Gating of IEC measurements by UHF signals

Figure 6: Gating of IEC measurements by UHF signals at 333 MVA transformer

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 by means of the UHF signal significantly.

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 probes (UHF 1 – UHF 2). Two probes are opposite 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.

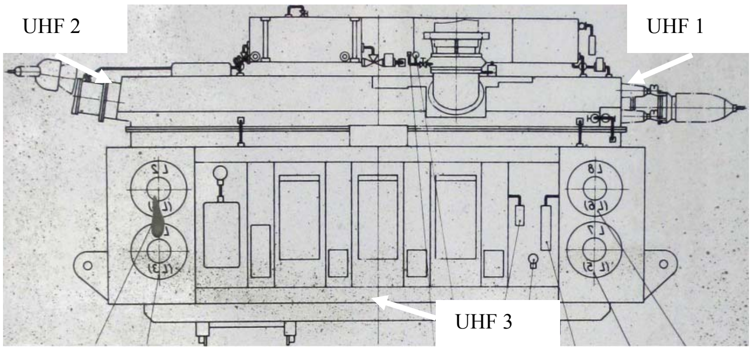


Figure 7: Positions of UHF Probes at 333 MVA single phase autotransformer

First, the so called dual port Performance Check was done, compare to paragraph 2. Artificial UHF impulses were injected at each probe 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 probe. The explanation by the transformer manufacturer was that there are tubes behind the oil filling valves directing the oil flow around the winding. According to the unsuccessful dual port Performance Check it could be stated, that the probes are electro magnetically decoupled from each other. Furthermore they might be also shielded against UHF pulses from internal PD.

But nevertheless, at nominal voltage, UHF signals from internal sources were detectable with all three probes. I.e. the internal PD cause UHF signals with higher energy content than the former artificial impulses. It can be concluded that the dual port Performance Check is thus just a worst-case estimation of the sensitivity. But in case the Performance Check is not successful, sensitive UHF measurements might still be possible. In Figure 8 the measured signals of the UHF probes are shown.

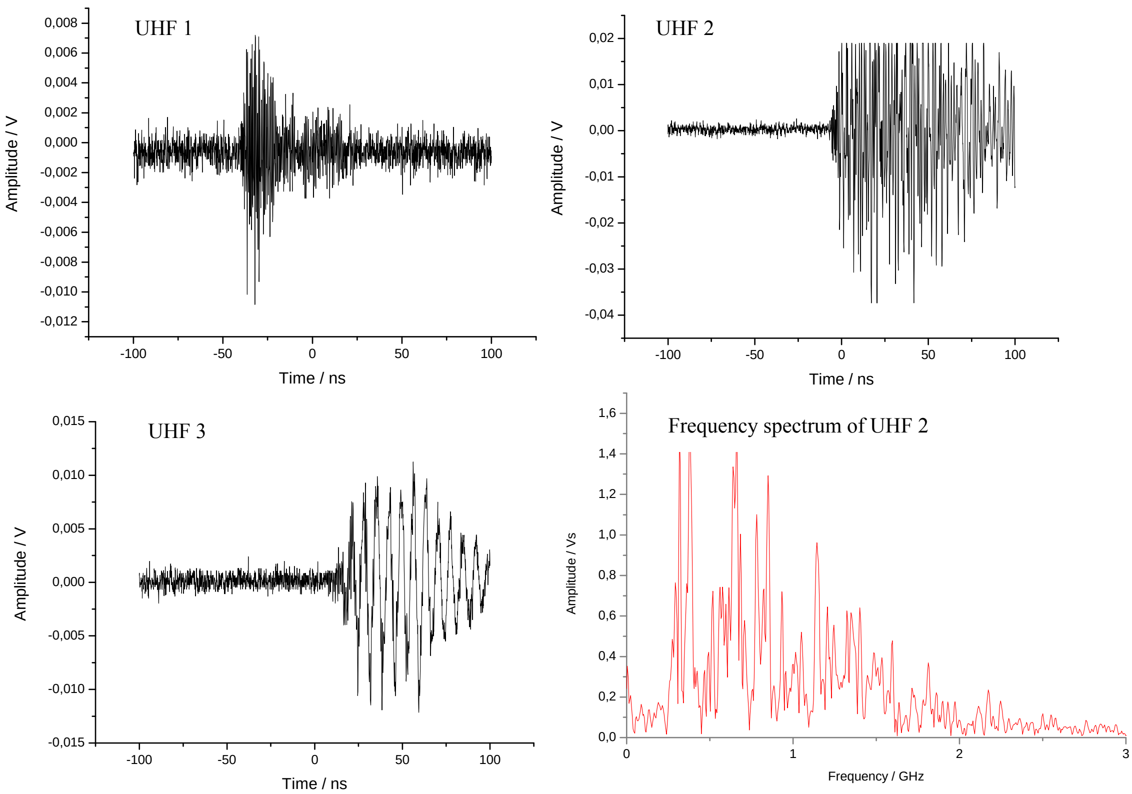


Figure 8: Measured run time differences between three UHF probes at different locations and Frequency spectrum of signal of probe "UHF 2" to prove broad-band emission

Recognizable are run time differences in the range of nano seconds (ns) between the signals. Taking run time differences caused by different lengths of measuring lines into account, a first estimation of the geometric PD location led to the tap changer. 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 with over 40 mV, whereas the other probes did not reach more than 10 mV. According to that, probe UHF 2 was used for triggering and determining the starting time for measuring run time differences. Simultaneous IEC 60270 measurements were highly disturbed by audible corona discharges. By using frequency analyses and phase related UHF PD patterns the UHF measurements were confirmed not to be affected by the external corona discharge.

An exemplary frequency analysis of the measured signal of probe UHF 2 proofed the shielding characteristic of the tank; see Figure 8 (bottom right). The signal features frequency content up to 2 GHz, as emitted by a broad band 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 (global system for mobile communications) since there are modulated carriers often. For further proof that the signals correlate to PD, PRPD´s of the signals were recorded, synchronized to the voltage supply of the measuring unit (LDS6/UHF). Similar to the IEC 60270 PD measurements typical patterns were visible, comparable to Figure 5. Phase stable UHF pulses showed correlation to internal PD.

PD also produces acoustic waves, which are measured with piezo-electric sensors installed at the outside 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 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 9 shows the positions of the used acoustic sensors (A1 – A6).

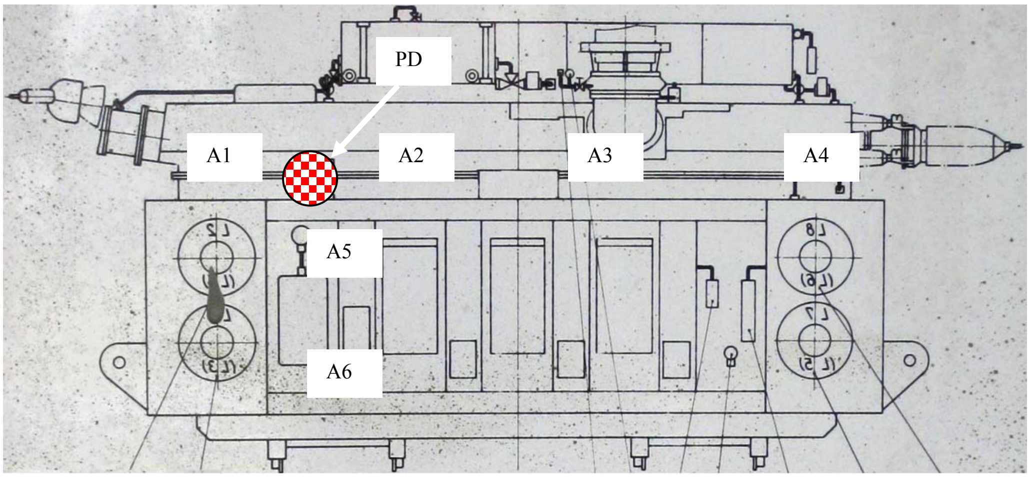


Figure 9: Position of acoustic sensors and localised PD source

The UHF measuring method is based on electromagnetic waves, which spread with approximately 2/3 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 run times of the individual acoustic sensors) result in a spherical area inside the transformer. With at least three acoustic sensors and corresponding run 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 steal tank to the sensor without any reflections. But furthermore the location process has also to deal with acoustic waves travelling faster in the tank wall than in the oil. The run times 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 starting point of the signal.
As illustrated in Figure 9, 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 run time differences and different localisation methods [5]. The different run time 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 proofed by an IEC triggered acoustic measurement in laboratory and the transformer is going to be detanked for repair.

4 CONCLUSION

The UHF PD measurement method is usable as single measurement and 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 probes are easily installed and are useable. 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 sometimes 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 for measuring UHF signals sensitively.
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. Overly strong noise on-site nevertheless might make this method unfeasible.
Run times measured in the UHF range can be used for geometrical PD localisation. The accuracy seems to be good enough to determine the phase where the PD is located. 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 at 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.

BIBLIOGRAPHY

[1] IEC 60270 High voltage test techniques – Partial discharge measurement
[2] K. Rethmeier, M. Krüger, A. Kraetge, R. Plath, W. Koltunowicz, “Experiences in On-site Partial Discharge Measurements and Prospects for PD Monitoring”, No: M-6, pp. 1279-1283, Proceedings 2008 International Conference on Condition Monitoring and Diagnosis, Beijing, China, 2008
[3] S.Coenen, S. Tenbohlen, S.M. Markalous, S. Strehl “Sensitivity of UHF PD Measurements in Power Transformers”, IEEE Transactions on Dielectrics and Electrical Insulation, Vol. 15, No. 6, pp. 1553-1558
[4] S. Coenen, S. Tenbohlen, S. M. Markalous, T. Strehl: “Fundamental characteristics of UHF PD probes and the radiation behaviour of PD sources in power transformer”, Proceedings 17th ISH, No: C-26, Cape Town, South Africa, 2009
[5] S. M. Markalous: “Detection and Location of Partial Discharges in Power Transformers using acoustic and electromagnetic signals”, Dissertation, Universität Stuttgart, 2006
[6] S. Coenen, S. Tenbohlen, S. M. Markalous, T. Strehl: “Performance Check and Sensitivity Verification for UHF PD Measurements on Power Transformers”, Proceedings 15th ISH, Paper-No: T7-100, Ljubljana, Slovenia, 2007
[7] A. Pfeffer, S. Coenen, S. Tenbohlen, S. M. Markalous, T. Strehl: “Onsite experiences with multi-terminal IEC PD measurements and UHF PD measurements”, Proceedings 17th ISH, No: C-51, Cape Town, South Africa, 2009
[8] S. M. Markalous, S. Tenbohlen, K. Feser: “Detection and Location of Partial Discharges in Power Transformers using acoustic and electromagnetic signals”, IEEE Trans. on Dielectrics and Electrical Insulation, Vol. 15, No. 6, pp. 1576-1583