Experiences with the Acoustic Localization of Partial Discharge in Liquid-Immersed Power and Distribution Transformer with help of UHF measurement technology

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I. Abstract

Power transformers are important components in every electrical power grid. Facing aging transformer fleets, the need for testing, diagnostics and reliable condition assessment becomes increasingly relevant. The quality and availability of the equipment used in electrical power networks are having significant influence on system reliability [1].

Detecting partial discharges in the insulation system of a power transformer at an early stage reduces the risk of total breakdown. In the last few years, alternative methods for PD measurement, such as electro-magnetic ultra-high frequency (UHF) measurements, have been developed. These methods are using special Transformer-UHF-Sensors and have proven to be robust against disturbances and are able to detect PD. They can also be combined with known methods like acoustic PD localization to improve the overall measurement performance, especially on-site. With this technique, detection and localization of partial discharge is possible by placing acoustic sensors on the surface of the transformer tank. The low level of interferences from outside the measurement setup constitutes one of the strengths of this method. A further advantage is the ability to identify the position of the partial discharge source, which is needed to estimate the risk and to enable a fast and effective repair.

II. Introduction

Partial discharge (PD) measurements on transformers are a well-established tool of quality control and an integral part of the factory acceptance tests. In the field, PD measurements on power transformers have been considered as not applicable for decades due to a lack of strategies to overcome the tremendous influence of external noise sources. On-site PD measurements are usually intensively interfered with by external disturbances, such as corona, from nearby systems and switching activity from the grid, respectively. Very often the amplitude of these signals exceeded the PD signals from inside the transformer tank by orders. Therefore, often no clear assignment of PD sources to the tested object is possible. However, a substantiated risk assessment requires such assignment and, even more, an identification and location of the PD fault. As the conventional PD measurement method according to IEC 60270 [2] is known to be sensitive to unwanted external interferences, UHF detection on or inside a transformers tank becomes more and more popular because of its high level of noise immunity [3].

The robustness against external interferences of the UHF method is mainly based on the fact that a transformer vessel in combination with graded bushings has an efficient shielding capability preventing broadband noise signals from entering the tank and reaching the UHF sensor [4].

Even in the case of a limited shielding capability due to ungraded bushings [5], the UHF method with a typical lower cut-off frequency of about 100 MHz is still beneficial. That is because it is usually not sensitive to impulses with only a relatively low frequency spectrum, like discharges in air e.g. corona.

Therefore the application of UHF PD measurement technology can help to verify internal PD in support of DGA data and can provide statistically relevant data to be used for PD pattern classification without overlapping external interferences [6]. Another feature of the UHF method is its ability to provide a precise trigger signal for acoustical PD localization. Since the introduction of UHF PD measurements on transformers it has been seen as a major disadvantage that UHF measurements cannot be calibrated in terms of PD charge magnitudes [7]. But for a risk analysis under on-site conditions the apparent charge value of a PD activity is of subordinated importance compared to PD type identification (pattern recognition) and the exact location of the fault. Recently a new CIGRE Working group (JWG A2-D1.51) has been initiated to work on recommendations for how to handle UHF measurements at factory and on-site acceptance tests of Power Transformers [8]

III. Currently used UHF PD Measurement Methods

A. Measurement Modes

Mainly two different types of UHF methods are applied:

- Tuned UHF narrowband or medium-band measurement with variable center frequency
- UHF broadband measurement with fixed bandwidth

1 Tuned UHF measurement with variable center frequency

Figure 1 shows the principle of the tuned UHF narrowband measurement with variable center frequency and bandwidth. A preamplifier is connected directly to the UHF sensor in order to prevent loss of sensitivity and reduce the effect of external noise over the length of the cable connected to the measurement equipment. Otherwise the measurement equipment has to be placed as near as possible to the sensor.

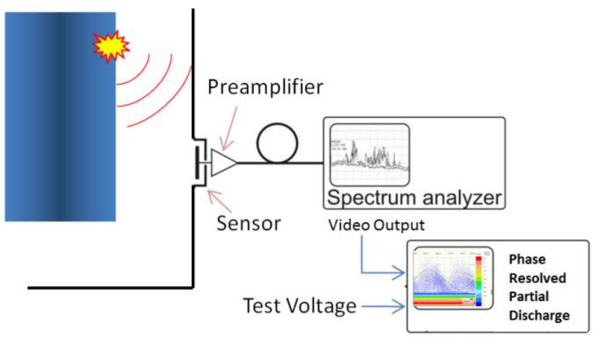

Figure 1: Example of a tuned UHF narrowband measurement with variable center frequency [9]

Figure 2 shows the spectrum analysis during a PD measurement in the frequency range of 0.1 - 1.8 GHz. The lower trace shows the background noise floor while the upper trace displays the mixture of PD signals along with sporadic external interference, displayed linearly in frequency and logarithmically in amplitude (peak hold measurement for a certain time).

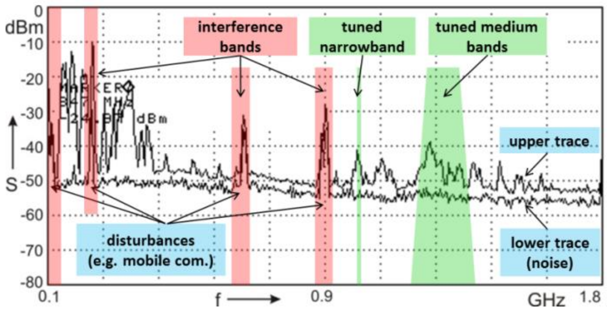

Figure 2: Signal relationships of proposed tuned UHF methods (schematic example) [10]

The frequency window in which PD can be measured depends on the combination of the defect, propagation path and the employed sensor. Ideally, a suitable measurement frequency window can be identified easily by visual observation of spectral areas in which a high signal-to-noise ratio (SNR) results in high measurement sensitivity.

Once such a window is found, a sensitive PD result can be obtained when the measurement systems center frequency is tuned accordingly. The bandwidth has to be set to a certain and suitable value of e.g. 1.5 MHz for a tuned narrowband measurement or e.g. 70 MHz for a tuned medium bandwidth measurement. The result (video output of the spectrum analyzer or other down converter systems) is that the time-domain PD signal is coupled out (Figure 1) and can then be displayed on a conventional PD measurement system which is synchronized to the high-voltage test waveform.

Once a phase-correlated pattern can be observed (Figure 15), it means that a PD source synchronous to the test voltage is active and should be further investigated. If no phase-correlated pattern can be found, it is probable that the signal is an uncorrelated external interference which is irrelevant. Even under difficult conditions with high levels of ambient interference, with some practice suitable frequency windows with good SNR can be found [9].

The selection of the center frequencies should be based on the individual resonant frequencies of the PD sensors determined comparable to GIS applications by the CIGRE sensitivity check on site [11].

2 Broadband UHF measurement

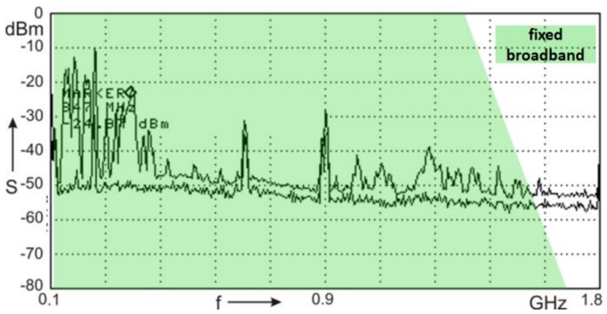

Figure 3: Bandwidth of fixed broadband UHF method (schematic example) [9]

Broadband UHF measurement with a fixed bandwidth is widely used, especially for monitoring systems. A schematic diagram of the PD signal spectrum measured across a bandwidth of several hundred MHz is shown in Figure 3. Here, the fixed broadband frequency spectrum is directly integrated and the signal variation is displayed directly in a phase-resolved PD pattern format.

A disadvantage of this method is the lower SNR. Even narrowband disturbances lead to a reduced sensitivity in a broadband measurement system. Advantages of this method are the relatively easy technical realization and the low effort for choosing the settings compared to the previously described narrowband method.

The different methods can be also combined together in one measurement system [12].

B. UHF Sensors

Two types of UHF sensors are commonly used on transformers - fixed installations of permanently mounted sensors and sensors for temporary use, inserted into a drain valve with sufficient diameter. Both types use the long experience of UHF sensors applied to gas-insulated switchgears (GIS) and adapt the sensor principle to the transformer.

For mounted sensors, a manhole or flange can be adapted, so that one or often more sensors can be permanently fitted into a transformer. The mechanical stability and permanent oil tightness has to be ensured. The permanent availability of the sensor makes it perfect for monitoring purposes, either by interval or permanently. For sensor placement spots, with presumably better signal reception, can be chosen, which can improve the signal-to-noise ratio of the received PD signals. By choosing a useful placement, a PD localization is also possible by using triangulation with different UHF sensors [13][14]. The authors consider the permanent installation of several UHF sensors in transformer housing a major trend in the future, at least for important units since installation cost and technical risk are low compared to the added value of having the ability to scan a transformer easily for internal PD or other discharge phenomena and the chance to locate the problem.

Figure 4: Drain valve sensor for insertion temporary into the transformer

In contrast to the fixed sensor, the portable drain valve sensor involves little effort and allows flexible on-site and factory testing. If one or more drain valves with sufficient diameter are available, a lance with a sensor on top can be inserted through the valve into the transformer (Figure 4). It must be noted that the described procedure is applicable for gate valves while the use of such kind of UHF rod sensors is not possible on bell-type valves. This should be considered during the specification process of transformer oil valves. The authors do recommend the use of gate valves and not to exclude the application of UHF method right from the beginning. The reception of the signal is done just by the sensor tip, so it has to reach into the tank beyond the wall. Also plates or other structural elements in front of the sensor can lead to a significant reduction of sensitivity. Additionally, the electrical field stress at the insertion point should be low – which usually is the fact, so that no dangerously high field strength can occur by inserting the lance. The sensor tip is rounded to reduce this risk further. Due to the fixed position of the valves in a transformer, a spot with presumably higher sensitivity cannot be chosen.

IV. The propagation behavior of acoustic PD signals in transformers

The acoustic effect of PD inside a transformer is typically measured by piezo-electrical sensors in the frequency range of tens of kHz up to hundreds of kHz [15]. Using the different arrival times of the acoustic PD signal at multiple sensors, algorithms can compute the location of the PD source.

Speed and damping of the acoustic waves are dependent on the transfer medium, frequency range and temperature [16],[17]. For example, the propagation speed decreases during the heat-up period of an transformer by approximately 15%, from about 1400 m/s at 20 °C to 1200 m/s at 80 °C.

The propagation path is often complex. Multiple propagation paths of the emitted sound wave are possible, as shown in Figure 5. Depending on sensor and PD location, multiple acoustic wave components of the same PD event are potentially detected by one sensor and overlay the direct oil signal as illustrated in Figure 6. The acoustic wave can be reflected by the tank wall, core, winding, flux shields and other components.

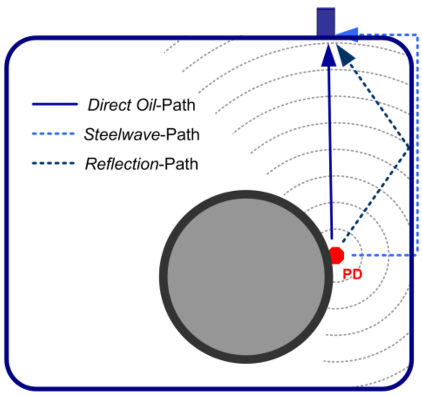

Figure 5: Possible propagation paths in the test object [18]

Components of the reflected wave will arrive at the sensor position later than the signal travelling a direct path. Furthermore, the acoustic wave can couple into the transformer wall and propagate through the steel of the tank. Due to the higher propagation speed in steel of about 3.000 - 5.000 m/s [15], the so-called steel wave signal can reach the sensor earlier than the waves following the direct oil path. This effect complicates the automated determination of the starting point of the direct oil signal.

The measurable direct oil signal at the sensor position depends on the intensity of the causative PD event [19] and on the damping on the propagation path. Therefore, the attenuation by core, winding, transformer board, flux shielding etc. should be as low as possible. For that reason, the search for sensor positions that ensure good signal quality is essential during measurement procedure. The knowledge about the inner structure of the transformer is helpful for a good positioning and repositioning of the sensors.

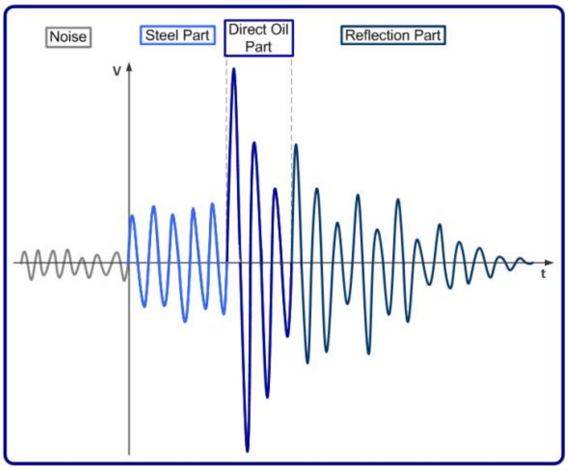

Figure 6: Acoustic PD signal components reflecting the propagation paths

V. Localization of PD using Acoustics

Different algorithms can be used to perform a time-based localization of PD. The input information used by the algorithms is the time of arrival of the signals propagating on direct oil paths to multiple sensors. The exact time of arrival has to be determined by evaluating the measured signal.

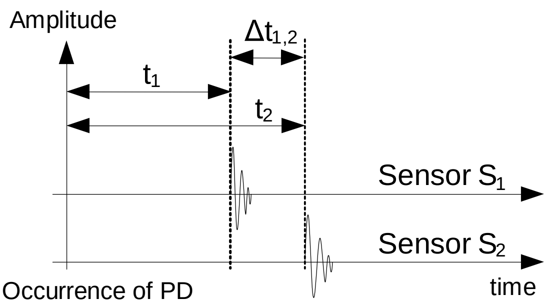

Figure 7: Absolute and relative times in a two-sensor-setup

A criterion for the starting point can be found e.g. by investigation of energy steps [20] or by threshold criteria [21]. The exact timing of the emission of the PD signal can be estimated e.g. by an electrical PD measurement according IEC 60270 or a measurement in the ultra-high frequency (UHF) range (see above).

The distance between sensor and source is calculated using the available propagation times and an estimated average propagation speed. With the determined distances and the sensor positions a geometrical localization of the PD source can be performed in several steps (Figure 8).

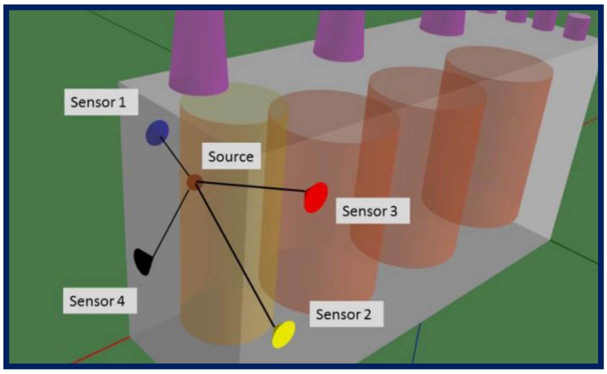

Figure 8: Principle of acoustic localization [18]

The arrival time (t_1) at a single sensor in relation to the PD occurrence leads to a surface in the shape of a sphere around the sensor position on which the PD source is supposedly located. The radius r depends on the absolute propagation time (e.g. t_1) and the propagation speed (Figure 9)

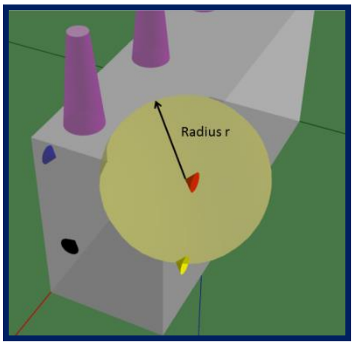

Figure 9: Spatial information from one sensor together with a UHF trigger

The position of the source can be specified with the information from a higher number of sensors. For this purpose several of the described geometrical shapes are intersected. The absolute propagation time of the signal at a second sensor leads to a second sphere. The resulting intersection shape is circular. In a further step, the absolute coordinates of the source can be estimated by intersecting the circulars of three sensors.

This procedure is shown in Figure 10. The figure shows the spheres around three acoustic sensors (black, yellow and blue). The resulting intersection circulars of the spheres are shown as blue rings. The estimated point of the acoustic source is displayed for three or more acoustic sensors.

The depicted method is based on a direct propagation path for the acoustic wave from source to sensor. As described above, the transformer cannot be considered as an empty box and the propagation speed is highly dependent on the signals travel path. For that reason, the model is always a simplification of the real setup inside the tank. Thus, also an inaccurate localization of the source position is possible.

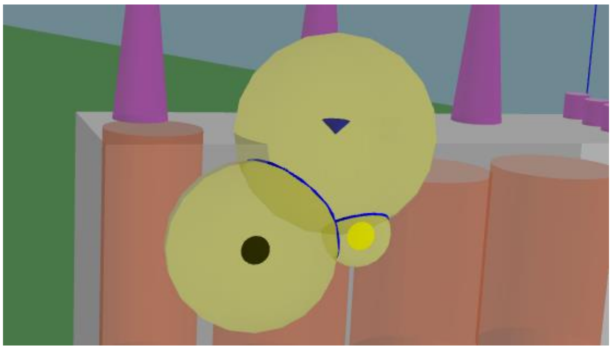

Figure 10: Source localization with three sensors using absolute times

To ensure reliable measurement results, a workflow is proposed that is based on an iterative relocation of the sensors with the intention to find positions with a minimal and undisturbed path between sensor and source.

VI. Case Studies

A. Comparison of measurement results in the UHF range and electric PD measurement according IEC 60270 performed at a measurement tap of a bushing

During a combined electrical and UHF PD measurement on a GSU rated >1100 MVA, a drain valve sensor as described above has been applied as to be seen in Figure 11.

Figure 11: UHF sensor connected to the tested transformer in the factory test laboratory

To confirm the basic assumption that a PD measurement inside the transformer tank is quite immune against noise signals or external PD, an immunity test has been performed. Therefore corona wires have been connected between two HV phases.

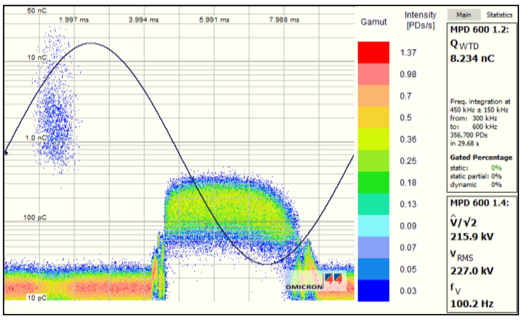

Figure 12: Pattern of an outer corona on a transformer

Figure 12 and Figure 13 compare the electrical PD pattern measured at the bushing tap of the one phase (Figure 12) and the synchronous reading of the UHF system, using a 1.5 MHz filter set to a center frequency of 490 MHz, inside the tank (Figure 13).

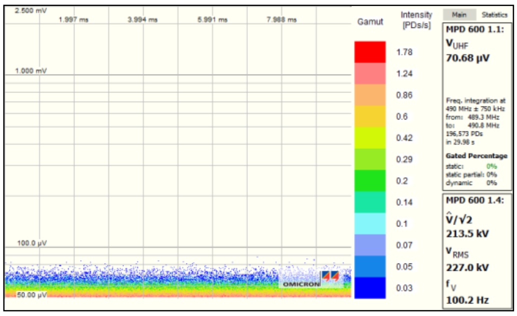

Figure 13: Corresponding synchronous UHF results to the outer corona on a transformer

It has been shown that the very intensive corona signals (about 8.3 nC) did not reach the UHF antenna – no signals were visible above the background noise floor of about 70 µV. Later on internal PD occurred on this transformer, which had been measured with the conventional PD measuring system and were detected as well by the UHF measuring system. Figure 15 shows the PD pattern measured at the bushing tap (Figure 14) and the synchronously detected signals at the UHF probe (Figure 15). Both show the same behavior. It is remarkable that a relatively low PD level of about 73 pC resulted in a UHF reading of more than 1000 µV, which clearly exceeds the basic noise level of the system. These results show the main principle of PD noise suppression by use of UHF PD measurement. External signals were not able to reach the inner antenna, while inner PD was detected with high sensitivity. [22]

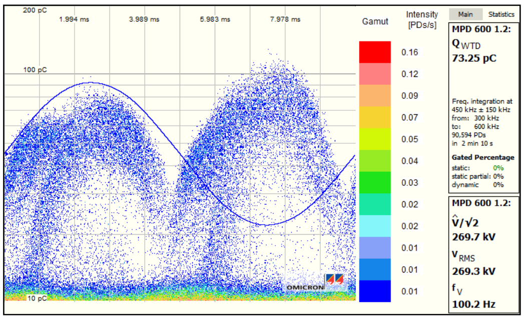

Figure 14: Pattern of internal PD inside a transformer [22]

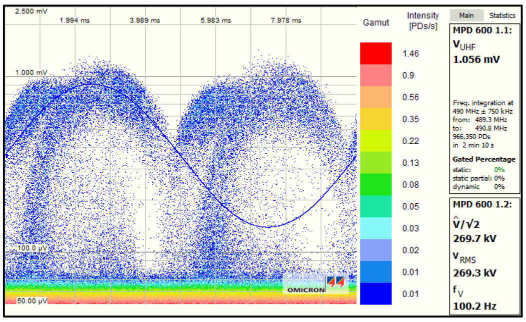

Figure 15: Pattern of this internal PD measured synchronously with UHF technology [22]

B. Case Study for combination UHF and acoustic location

The second investigation was performed on a 230 kV/20 kV transformer of 100 MVA in a manufacturer's test field. The UHF and conventional electrical PD measurement revealed quite comparable PD patterns shown in Figure 16. Both signals were potentially qualified to trigger an acoustical localization system.

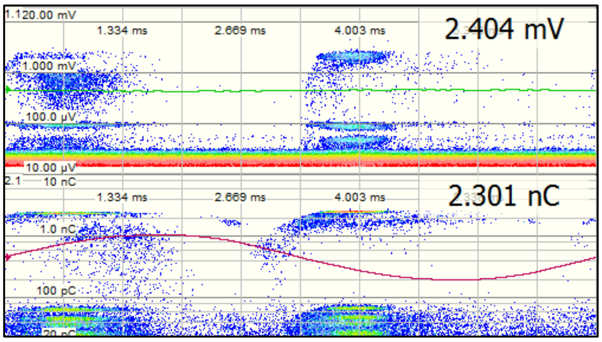

Figure 16: Simultaneously measured PD pattern of the UHF system (top) and conventional PD detector at the bushing tap (bottom)

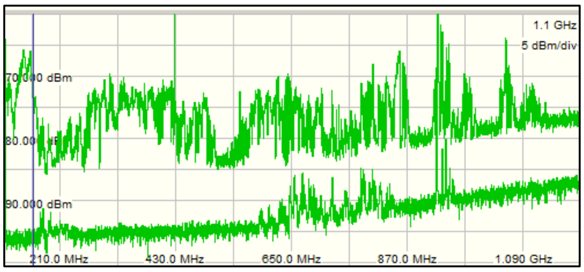

Figure 17: UHF Frequency sweep of the spectrum inside of the transformer and the measurement filter used shown as grey bar at 159.5 MHz

The UHF measurement was performed by using the narrowband acquisition method with a bandwidth of 1.5 MHz. The center frequency of 159.5 MHz was chosen based on the evaluation of the frequency sweep shown in Figure 17, right. The highest signal energy of the UHF spectrum is shown as the upper line representing the pulses - including the PD - while sinusoidal or continuous wave (CW) disturbances are shown in the lower curve. The measurement frequency can now be tuned into an area showing a large distance between both lines. This method turned out as being very effective to optimize the signal-to-noise ratio during an UHF PD measurement.

Figure 18 shows the 3D model of the transformer with the final sensor positions and the electric-acoustic test setup.

After optimizing the UHF signal quality (by choosing a center frequency) the pulses detected by the UHF system were used to trigger the acoustic PD localization. The evaluated time delay led to PD source positions on the outer surface of the tap winding between winding and tap changer as shown in Figure 19.

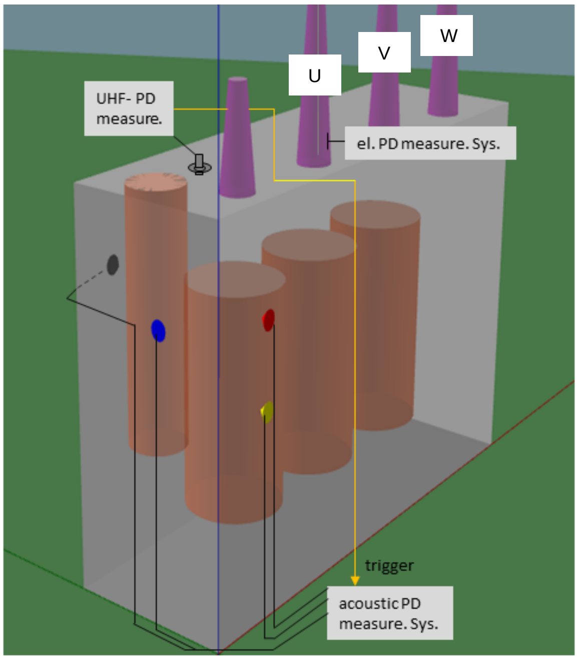

Figure 18: Test setup (UHF, el. and acoustic PD)

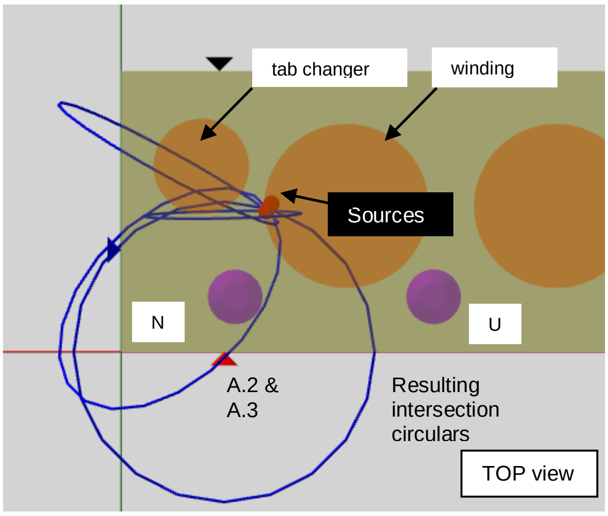

Figure 19: estimated PD source location and some intersection circulars (left)

The subsequent inspection of the transformer confirmed a close match of the defect and the estimated PD source [23].

VII. Conclusion

This paper describes the basic idea of time-based acoustical localization of PD faults in power transformers and using UHF the measurement technique. The PD signals are captured using three or more piezoelectric acoustic sensors, magnetically mounted on the tank at different locations. For localizing the source, the time delays between the recorded acoustic signals and a UHF signal are used to get information about the propagation of the acoustic signal inside the transformer tank and the distances between signal source and sensors. The received sensor signals are processed to obtain the difference between the signal arrival times at each sensor.

Also shown is the typical UHF partial discharge measurement method. Among the present UHF methods, the tunable band pass method with visual selection of the measurement frequency, in conjunction with a broadband preamplifier directly mounted at the PD sensor, allows the most sensitive measurements. The broadband method leads to a measurement system with minimum configuration effort.

Case studies of successful PD localization of a significant PD source have been shown. The procedure and successes of an acoustical measurement with triggering in the UHF range has been shown. The results are analyzed and visualized by using a 3D model.

UHF PD measurements in transformers can lead to substantial benefits, especially on-site, compared to conventional measurements, but the sensitivity of the placed sensor has to be ensured.

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IX. Zusammenfassung

Leistungstransformatoren sind wichtige Komponenten in den Versorgungs- und Übertragungsnetzen. Mit Blick auf das zunehmende Alter der Transformator erhöhen sich die Ansprüche an Prüfung, Diagnose und zuverlässige Zustandsbeurteilung. Die Qualität und Verfügbarkeit der Betriebsmittel beeinflusst maßgeblich die Zuverlässigkeit des Gesamtsystems. [1]

Das frühzeitige Detektieren von Teilentladungen im Isoliersystem eines Leistungstransformators kann hier das Risiko von Ausfall und Schaden verringern. In den letzten Jahren wurden daher weitere Messverfahren entwickelt wie z.B. das TE-Messverfahren im UHF-Bereich (Ultrahochfrequenz). Bei dieser Methode werden mit spezielle UHF-Sensoren die TE Signale am erfasst. Dabei hat sich die Methode als sehr robust gegenüber externen Störern gezeigt und kann daher auch Vor-Ort eingesetzt werden.

In der Kombination mit bekannten Methoden wie akustische TE Ortung ergeben sich neue und optimierte Lösungen für die Vor-Ort Diagnostik. Durch eine robustere und genauere Ortung kann das Risiko besser abgeschätzt werden oder Wartungsabläufe optimiert werden.

Dieses Paper gibt einen Überblick über die UHF-TE-Messung und akustische Messung an Transformator. Anhand von praktischen Beispielen wird die Messung im UHF-Bereich und die Kombination mit der akustischen Ortung gezeigt.