Acoustic localisation of partial discharge in power transformers

Practical experiences with and without the help of UHF measurement technology

ABSTRACT

Detecting partial discharges in the insulation system of a power transformer at an early stage reduces the risk of total breakdown. One method to detect partial discharges is acoustic measurement. With this technique detection and localisation of partial discharge is possible by placing acoustic sensors on the surface of the transformer tank. The low impact of electrical interferences from outside the measurement set-up constitutes one of the strengths of the acoustic 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. The sensitivity and accuracy of the PD localisation can be improved with a combination with conventional electrical measurement or with Ultra High Frequency (UHF) measurement method. Since the UHF measurement method is more advantageous for measurement environments with heavy interferences in the field, the combination with acoustic localisation proves to be useful even in challenging field situations. This article describes the application of this procedure illustrating it with different practical examples.

KEYWORDS

power transformer, partial discharge, acoustic localisation, electrical trigger, UHF range

Introduction

The localisation of Partial Discharge (PD) faults in transformers is often necessary when such incipient faults are identified. The measurement of partial discharge level in accordance with IEC 60270 [1] is a procedure established throughout the world for quality assurance of transformers and is performed as part of the today routine measurements at the manufacturer‘s factory. If the occurrence of PD in the transformer has been determined during such a measurement, it is a matter of urgency to localize the fault, which is often very small, as quickly and accurately as possible. Similar applies to transformers in the field. Here, PD detection and localisation procedures are generally initiated as a result of corresponding indications obtained from the Dissolved Gas-in-oil Analysis (DGA) as well as from

PD monitoring. A precise localisation can help to optimize the production of power transformer or can help by an effective maintenance during operation.

> ❞ Detecting partial discharges in the insulation system of a power transformer at an early stage reduces the risks of harm to the insulation and transformer failure

An established procedure for localisation of PD faults in transformers involves acoustic localisation of the PD signals using several piezoelectric sensors that are attached to the outside of the tank wall. A combination with conventional electrical measurement or with UHF measurement method can improve the sensitivity and the accuracy of the PD localisation. Since the Ultra High Frequency (UHF) measurement method is more advantageous for measurement environments with heavy interferences in the field, the combination with acoustic localisation proves to be useful even in challenging field situations. The application of this procedure is described in this article, also using different practical examples.

Partial discharge in high-voltage equipment

Partial Discharges (PD), as defined by IEC 60270 [1], are localized dielectric discharges in a partial area of an electrical insulation system under high electric field intensity. PD are generally measured in picoCoulombs (pC). These discharges can harm the insulation and might lead to a total destruction of the asset over time. To prevent such a sudden breakdown and carry out pre-emptive repairs, PD can be measured and evaluated.

PD measurements are a worldwide accepted tool for quality control of high voltage apparatus. Outside screened laboratories PD signals are very often superposed by noise pulses, a fact that makes a PD data analysis more difficult. The handling of disturbances on-site is one of the main challenges when measuring PD.

The propagation of acoustic signals in transformers

Partial discharges inside or on the surface of an insulation medium emit part of the energy that they release as a sound wave. At first, the sound wave propagates equally in energy in all directions, while the propagation speed depends on the transmission medium and its respective temperature, as well as on the sonic frequency in it. The amount of the acoustic signal energy that is able to reach the tank wall is determined to a large extent by the propagation paths of the wave. The constructional structures inside the transformer attenuate the sound (low-pass); however, the attenuation degree differs considerably between the various materials (pressboard, wood, paper, steel, oil, etc). The sound signal may reach the sensor from the PD source along various paths – of different transmission speeds – as a result of reflection and refraction phenomena. Depending on sensor and PD location, multiple acoustic wave components of the same PD event are potentially detected by one sensor and overlay the signal directly propagated through the oil as illustrated in Figure 1.

The measurable signal directly propagated through the oil, which contains the searched runtime information, depends on the intensity of the causative PD event and on the damping on the propagation path. Therefore, the attenuation by internal parts like core, winding, transformer board, flux shielding, etc. should be as low as possible. In this case the propagation speed can be estimated close to the speed of sound in oil (25 °C, 1400 m/s), so the search for sensor positions which ensure that the propagation path is mainly through oil and a good signal quality is

> ❞ The combination of UHF measurement with acoustic localisation proves to be useful even in environments with heavy interferences in the field

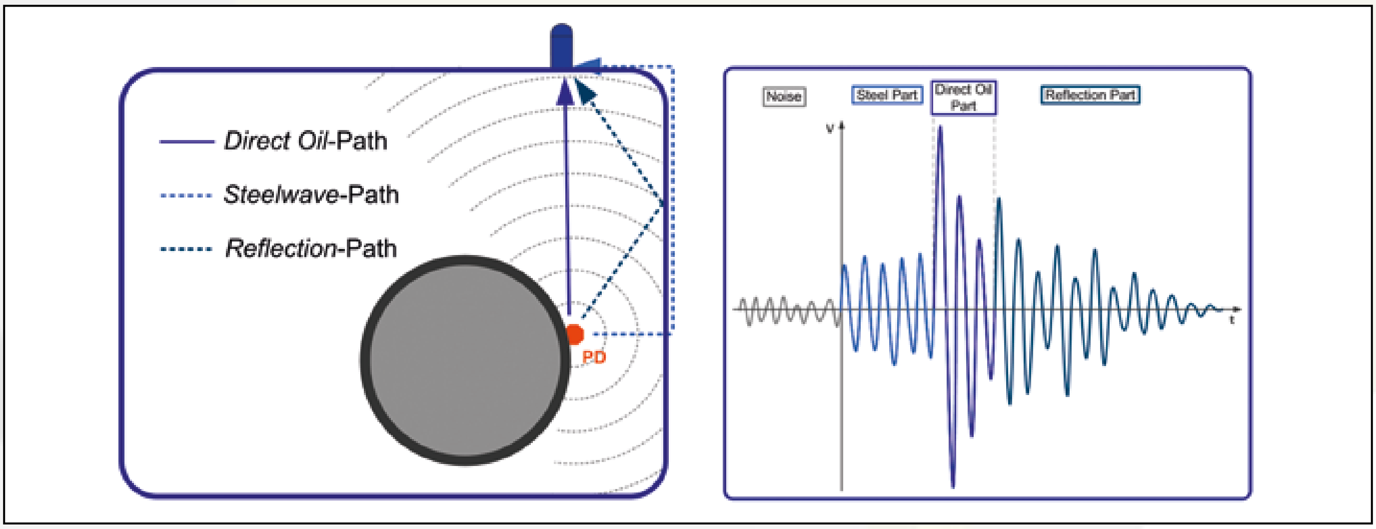

Figure 1. Possible propagation paths of the acoustic PD signal (direct oil-path, steel-wave path and reflection path)

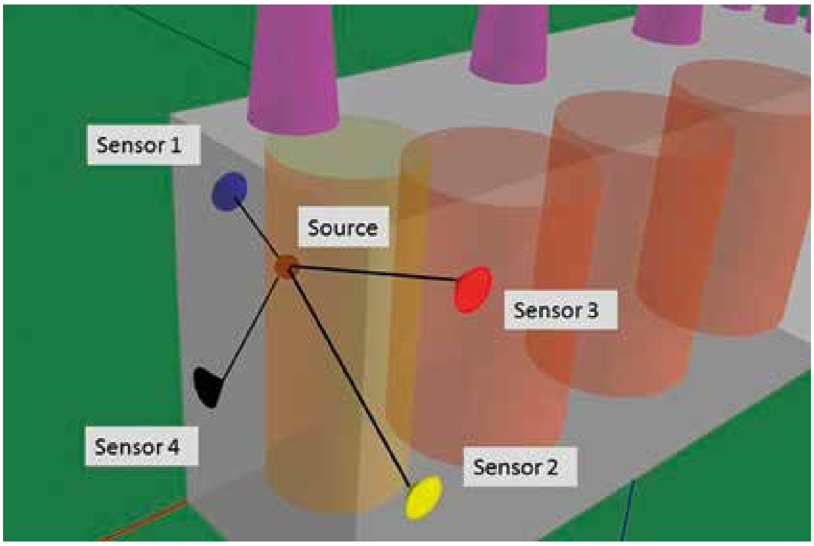

Figure 2. Principle of acoustic PD localisation with external sensors

> **Searching for sensor positions which ensure that the propagation path is mainly through oil and a good signal quality are essential during the measurement procedure**

essential during the measurement procedure. The knowledge of the transformer inner structure could be helpful for good positioning and repositioning of the sensors.

Runtime-based localisation of PD sources

The localisation of PD sources is performed by means of the differences in the runtime of the acoustic signal between the fault location and various sensors. Possible fault locations are calculated from the signal runtimes measured, using the speed of sound and the known geometrical positions of the sensors on the tank wall.

Exact determination of the signal start time is particularly important. Reliable determination of the starting point of the signal is usually only possible if there is an adequate signal quality. Positioning of the sensors with good contact is therefore very important in choosing locations on the wall at which the measurements can be taken with a good signal-to-noise ratio and low signal attenuation. Familiarity with the internal structure of the transformer and experience in performing such measurements are advantages here.

With regard to the localisation and the visualisation of the obtained results, a distinction can be made between measurements with an acoustic and with an electric trigger. In the first case, an acoustic sensor is used to determine the reference point in time. In such a case, only the time offset ($\Delta t_{1,2,n}$) between the sensors is available for calculation, which leads to an equation system based on the time difference approach. In addition to the pure acoustic method, the information on the electrical detected PD impulse can be used as time reference for the acoustic measurement since the electrical propagation speed is significantly higher (by a factor of about 100,000). Naturally, this requires a precise synchronisation between a PD detector and the localisation system. In such a case, the equation system used for localisation is based on the absolute time approach. Figure 3 represents the available times for both procedures respectively; however, for the sake of simplicity only two acoustic sensors are shown.

The runtime t_1 of a single, electrically triggered sensor (see Figure 4, left) produces a sphere around the sensor position. The spherical radius can be derived from the product of the sound velocity and the measured runtime. Every point on the surface of the spherical surface may represent a theoretical PD fault location inside the tank.

In case of a purely acoustic measurement, the signal of a single sensor provides too

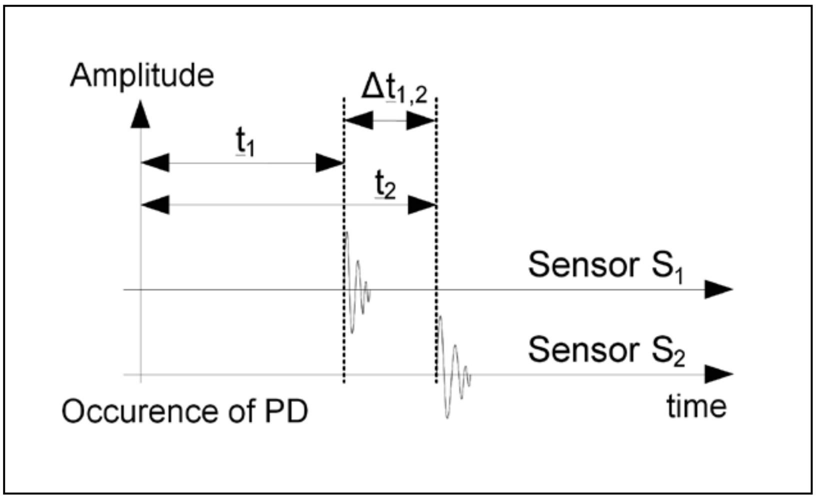

Figure 3. Absolute and relative time values for the acoustic sensors

> **Possible fault locations are calculated from the measured signal runtimes, using the sound speed and the established geometrical positions of the sensors on the tank wall**

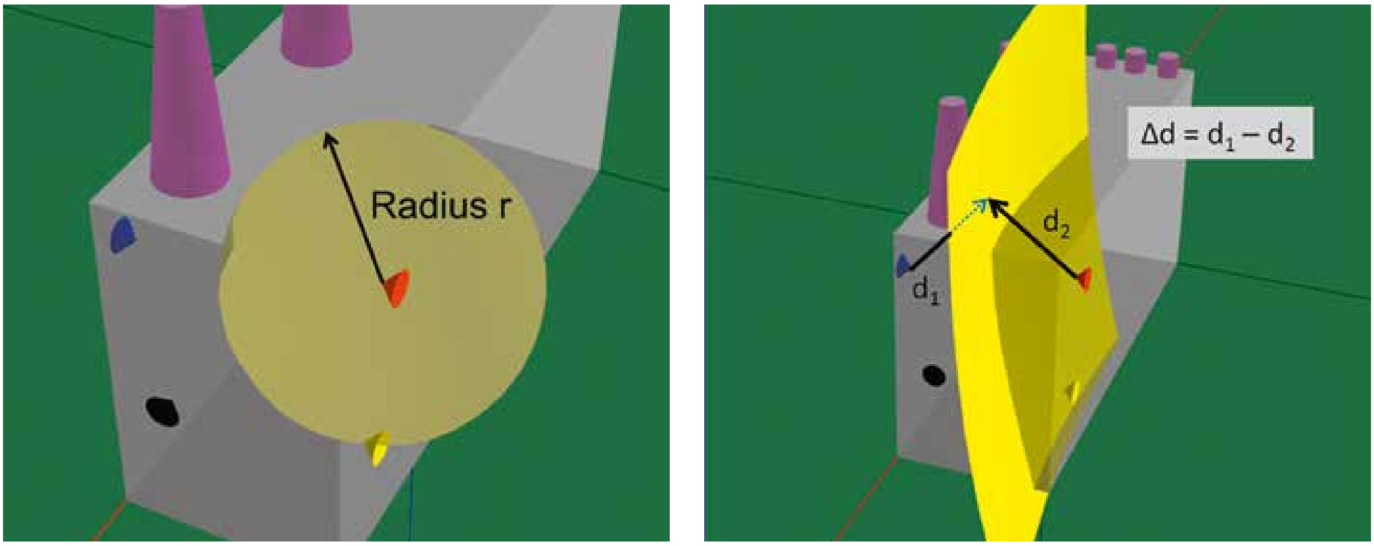

Figure 4. Possible positions of a PD source for an electrically triggered sensor (left) and with a purely acoustic measurement using two sensors (right)

little information for a reliable detection. Only when a second sensor is used, the time difference $\Delta t_{1,2}$ can be calculated. In this case the PD source can be located on a hyperbolic plane between the sensors, as shown in the right-hand section of Figure 4.

The significance of the results generally increases with the increasing number of sensors, as the number of possible solutions is reduced. This is based on the fact that the surfaces respectively related to additional sensors overlap with those existing previously, and subsequently form circular lines, as an example.

The spatial coordinates of the PD source can be estimated, if the ring-shaped lines intersect in one point, as shown in Figure 5, by using three acoustic sensors and an electrical trigger. In the case of pure acoustic measurement, additional surfaces, which overlap each other, are analogously formed, and their intersections may in turn be potential locations of the acoustic source and thus of the PD fault.

> **The significance of the results generally increases with the increasing number of sensors, as the number of possible solutions is reduced**

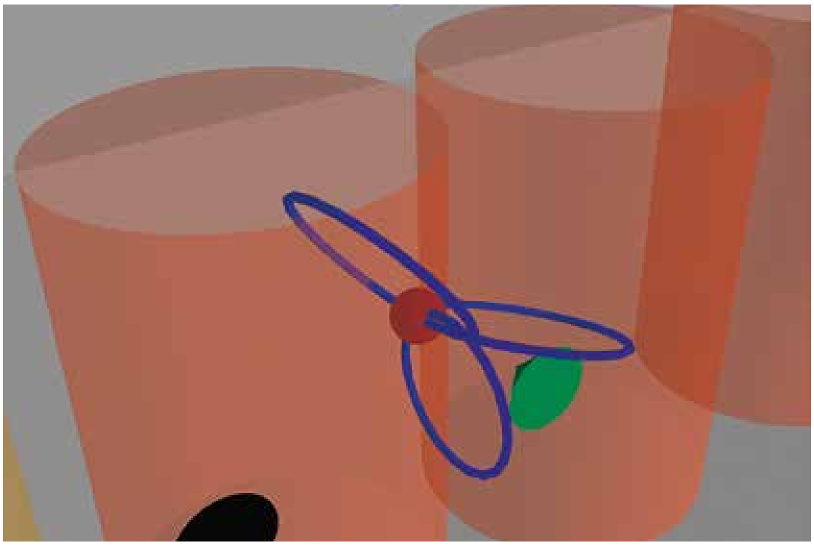

Figure 5. Pinpoint localisation of the PD location by intersection of three ring-shaped lines

Since the above-described method is based on the assumption of a direct acoustic propagation path with a defined sound velocity between the PD source and the sensor, it is not always possible to localise precisely the source in practice. The model assumption must be considered as a highly simplified image of the real conditions inside a transformer and as a result, inaccuracies during the localisation may occur. It has therefore become common practice to optimise the position of the sensors on the tank wall iteratively. Here, the aim of positioning the sensors is to find the optimal sound path between the source and sensor.

Currently utilized UHF procedures for PD measurement

Mainly two different types of UHF methods are applied:

- Tuned UHF measurement with variable centre frequency
- UHF broad band measurement with fixed bandwidth

UHF measurement with tuned test frequency

The principle of the tuned UHF narrow band measurement with variable centre frequency is shown in Figure 6. The UHF signal, which is measured by an antenna type sensor, gets amplified and is displayed on a spectrum analyser.

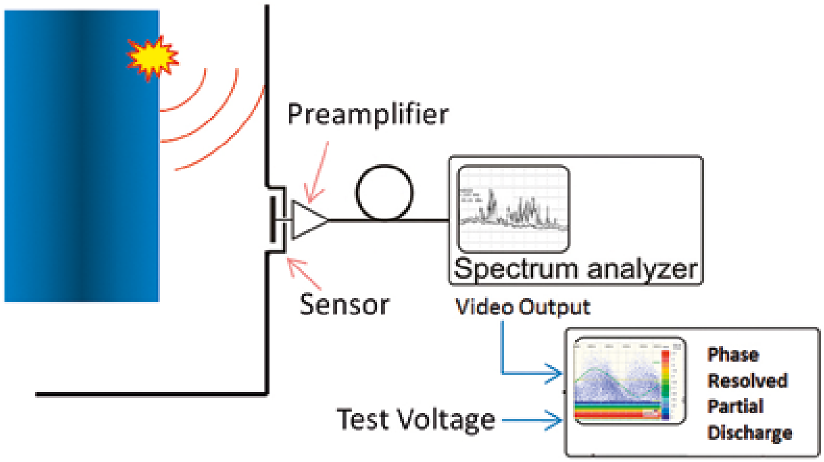

Figure 6. Example of a tuned UHF narrow band measurement with variable centre frequency

In Figure 7, the display of a spectrum analyser for the measurement range from 0.1 GHz to 1.8 GHz is shown. The lower trace of the spectrum shows the noise floor including the constantly active external signals. The upper trace shows the combination of PD signals and sporadic external interferences. With the frequency linearly depicted, the amplitude is displayed on a logarithmic scale. The shown frequency spectrum was created over a period of 1 minute, considering the maximum value. The largest distance between the upper and lower traces represents the ideal test frequency. It might be helpful to feed an impulse via a second UHF sensor prior to the measurement in order to identify frequency ranges that are suitable for a highly sensitive measurement.

When this range has been established, the centre frequency is adjusted accordingly and the bandwidth of e.g. 3 MHz (tuned narrow band) or higher (tuned medium band) is selected. This signal can subsequently be displayed as a phase correlated pattern on a conventional PD measurement system that has been synchronised with the test voltage.

> **The model assumption must be considered as a highly simplified image of the real conditions inside a transformer, which may lead to inaccuracies during the localisation**

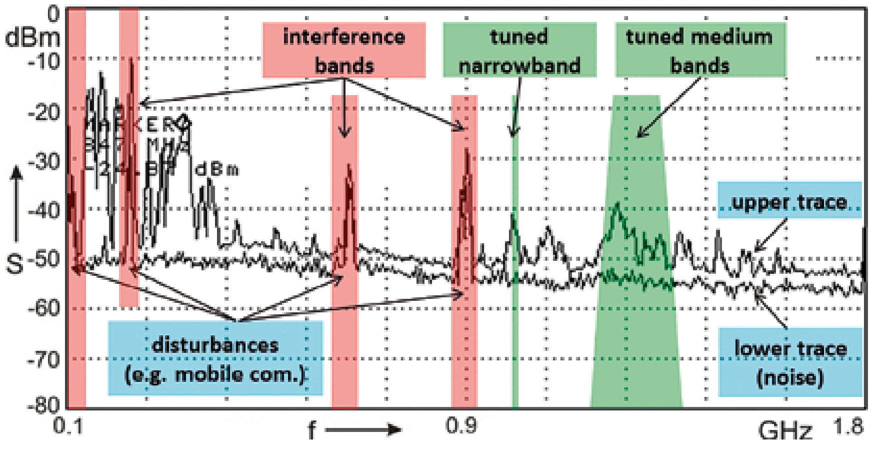

Figure 7. Spectrum of the measured signal at the UHF sensor (exemplary schematic depiction)

> **Combination of different detection methods provides a system adaptable to the respective requirements.**

UHF broadband measurement

The UHF broadband measurement with fixed band width is often used in monitoring systems.

Figure 8 shows a schematic depiction of PD signal spectrum that has been measured across a bandwidth of several hundred MHz.

The envelope curve of the amplitude signal of the broad band measurement with fixed bandwidth is transferred directly to the PD measurement system and displayed as a correlated PD pattern.

A disadvantage of this broadband measurement procedure is the often low distance between the signal and noise because in the case of such measurement systems, even narrow banded noises in the measurement range result in a reduced sensitivity. The advantages of the procedure are a comparatively easy technical feasibility and the minimal set-up effort in comparison to the previously described narrow band procedures.

Combination of different detection methods provides a system adaptable to the respective requirements. On the one hand, it allows an easy and fast performance of measurement under basic conditions with a relatively low set-up effort. In the environment with interferences, the adjustable test frequency can ensure highly sensitive measurements.

Example 1: Measuring example of a pure acoustic PD location

A 500 MVA power transformer showed a significant increase of hydrogen (H2) and methane (CH4) a few months after installation, which are typical key gasses for PD activity. A pure acoustic measurement was

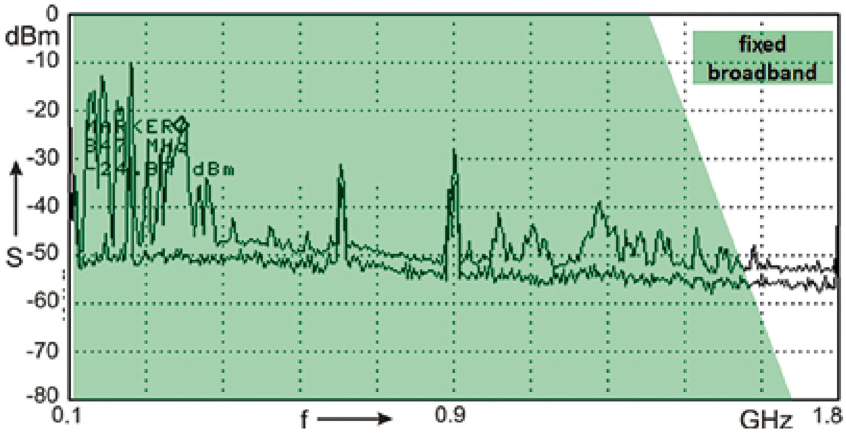

Figure 8. UHF broad band measurement with fixed bandwidth (sample schematic depiction)

> Detection of acoustic signals on the tank wall can be impeded by magnetic shunts which are known to have a significant sound damping effect

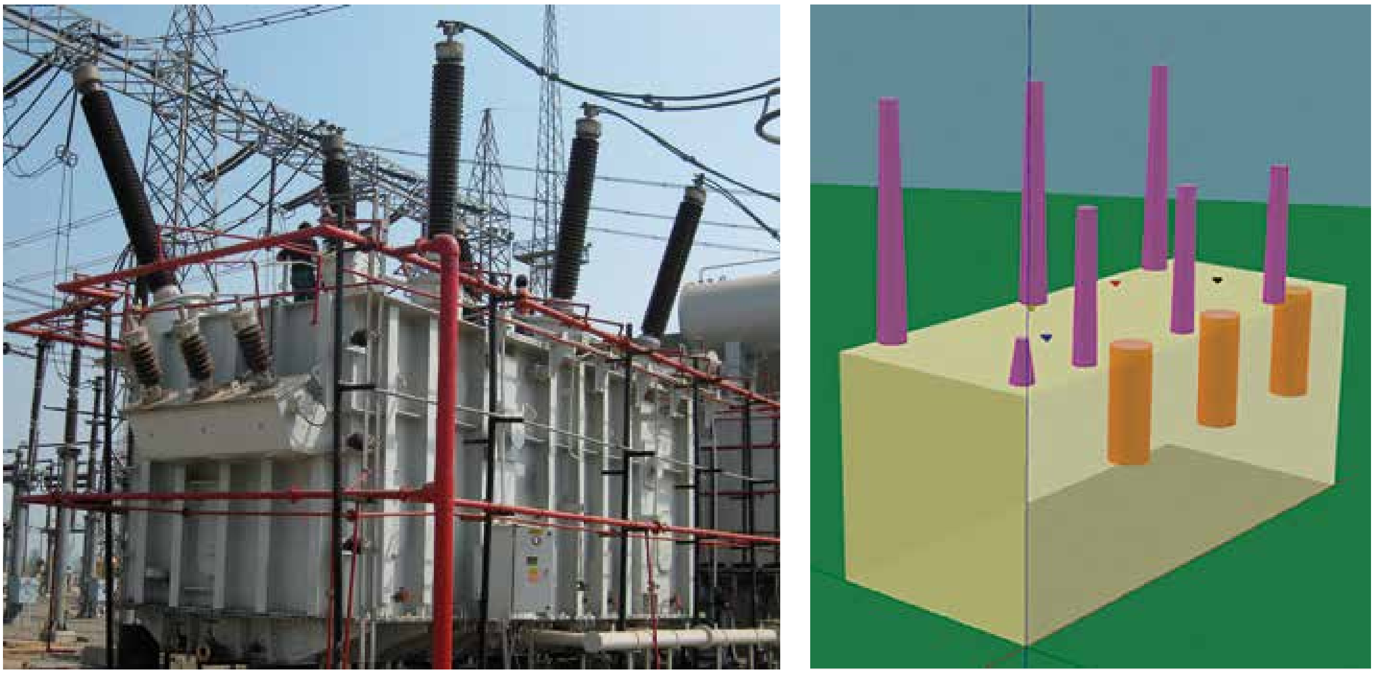

Figure 9. The unit under test and its representation in the localisation software, with sensors visible at the top and the three tap changer compartments highlighted in brown

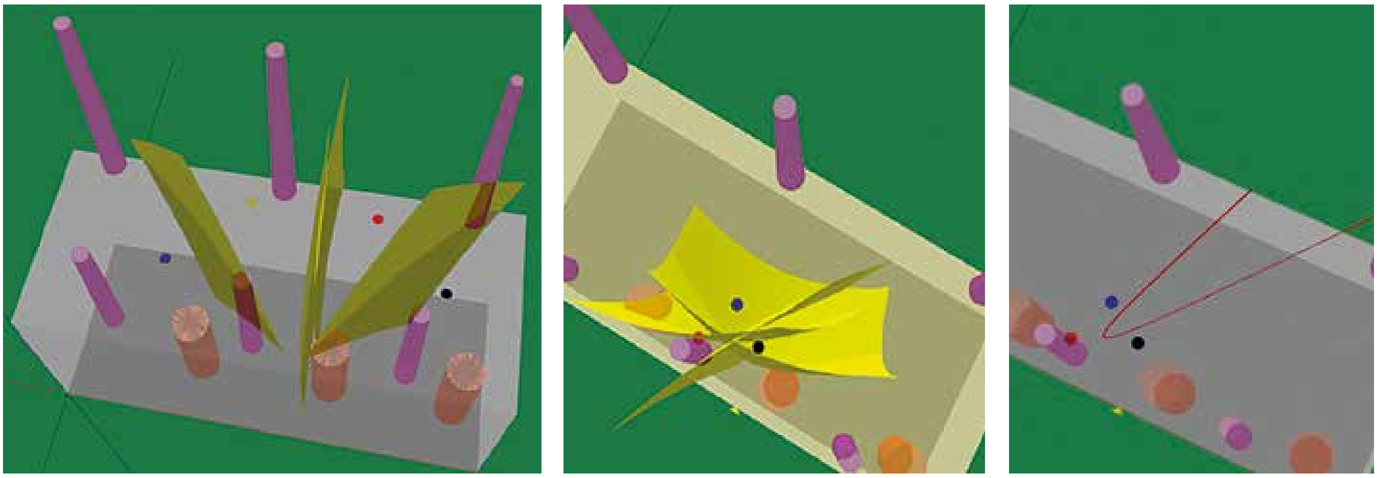

Figure 10: Results obtained with initial sensor position (left) and after sensor rearrangement (middle - in hyperbolic view; right - in line view)

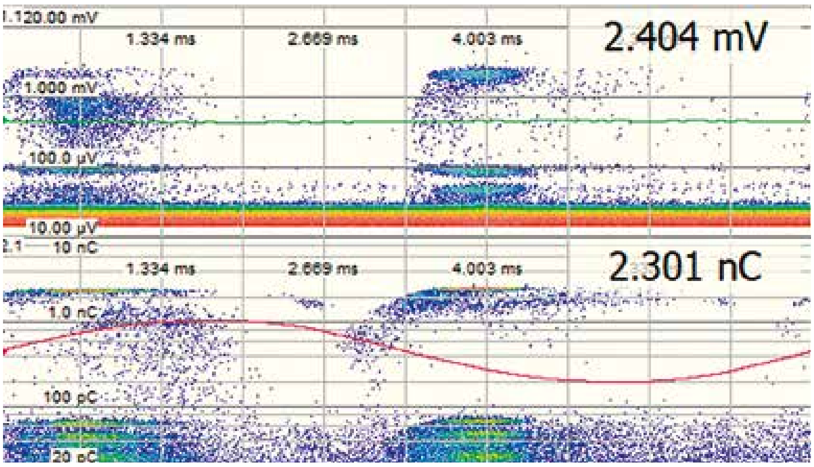

Figure 11: Synchronous UHF (above) and conventional (below) measurement on the defect transformer with the MPD-System

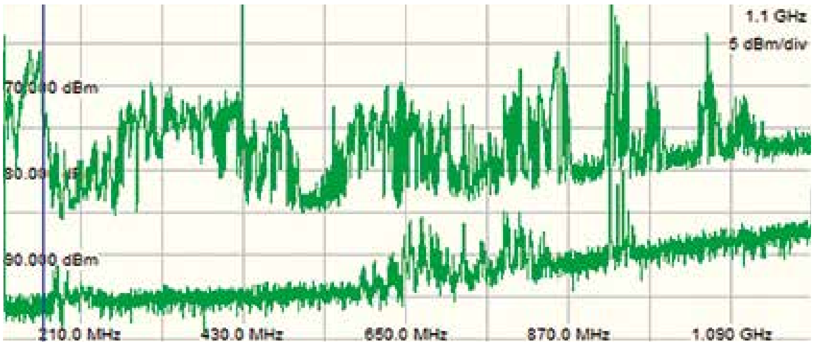

Figure 12: UHF frequency sweep of the measurement signal at the UHF sensor with the MPD 600 together with the UHF 620. Measurement frequency at 159.5 MHz (see grey bar)

performed, using PD localisation system PDL 650. Figure 9 shows the transformer and its modelling in the localisation software.

During the initial PD location, electrical triggering could not be utilised. Furthermore, detection of acoustic signals on the tank wall was not possible, presumably due to the magnetic shunts which are known to have a significant sound damping effect. Thus, the acoustic sensors had to be attached on top of the transformer.

The measured results with the initial sensor arrangement indicated a PD location at the middle phase, close to the tap changer and 220 kV bushing (see Figure 10, left). After the rearrangement of the sensors closer to the expected PD spot, an improved signal quality and higher sound levels were achieved. The resulting surfaces representing the mathematical solutions of the localising equations can be seen on the right-hand side of Figure 10, confirming the initial expectation about the PD location. An internal inspection of the tap changer connection through a man-hole revealed defects of different insulation elements which have been replaced. The transformer has been put back into service and is now operating without any indication of remaining PD activity. The gas concentration remains stable.

Example 2: Measuring example of an acoustic PD localisation with UHF triggering

The second measurement was performed at a 230 kV/20 kV transformer with a nominal power of 100 MVA. In this case, the UHF measurement and the conventional electric measurement were performed parallel with an MPD 600 and an UHF 620 converter. The phase-separated discharge pattern of both signals is shown in Figure 11. Here, the signals of both electric and UHF measurement would be suitable as the trigger signal.

> ❞ Received sensor signals are processed in order to obtain the difference between the signal arrival times at each sensor

The frequency spectrum (Figure 12) shows potentially good measuring ranges from 130 MHz to 160 MHz and from 300 MHz to 450 MHz. The centre frequency was selected based on the evaluation of the frequency spectrum, so the UHF measurement was performed with a narrow band filter, using a bandwidth of 1.5 MHz and a centre frequency of 159.5 MHz.

The 3D transformer model (including windings, bushings and the tap changer) and the acoustic sensors of the PD location system can be seen in Figure 13, which also illustrates the position of the UHF sensor and the conventional measurement at the bushing tap.

The UHF signals were used as an electrical trigger for the acoustic fault localisation. The measured values of the acoustic system showed a potential fault between the tap changer and its close winding (Figure 14).

After opening the transformer, the measured source location could be confirmed and repaired.

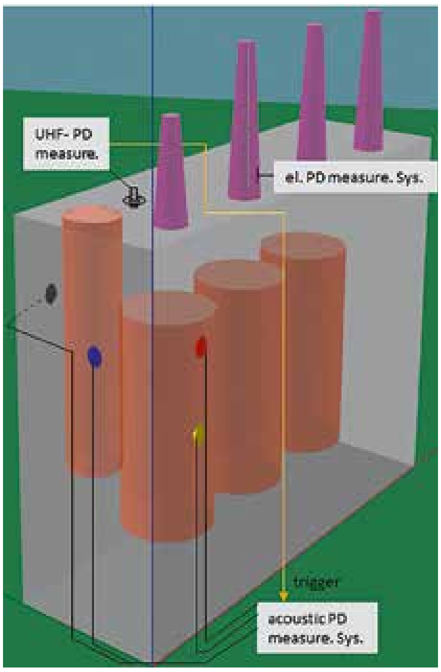

Figure 13: Measurement set-up, including UHF sensor, electric coupling at the bushing tap, and acoustic PD localisation system

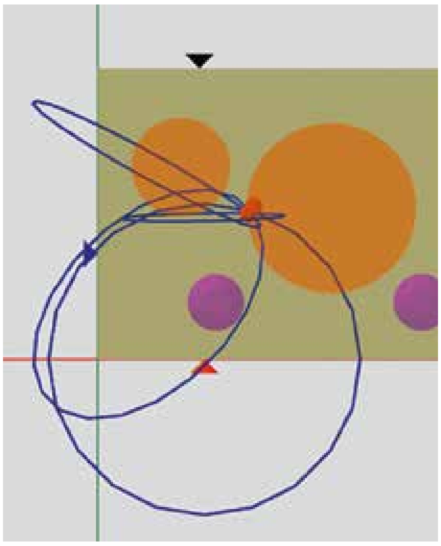

Figure 14: Detected PD sources with the transformer in plain view

> **Both described approaches can lead to a successful PD fault localisation while modern analysis tools, such as visualisation of a 3D power transformer model, facilitate the localisation of PD faults**

Conclusion

This article describes the basic idea of the time based acoustical localisation of PD faults in power transformers and similar equipment. The PD signals are captured using three or more piezoelectric acoustic sensors, which are magnetically mounted on the tank. To localise the source, time delays between the recorded acoustic signals or between an electrical signal and the acoustic signals are used to obtain information about the propagation of the acoustic signal inside the transformer tank and the distances between the signal source and sensors. The received sensor signals are processed in order to obtain the difference between the signal arrival times at each sensor.

In addition to the acoustical measurement, a parallel electrical PD measurement can be used to obtain an electrical trigger signal. The combination of electrical and acoustic measurement can improve the quality ensuring higher reliability, accuracy and sensitivity of the measurement. This can be essential for the success of an accurate localisation. Alternative to the electrical measurement through the bushing taps or with external coupling capacitors, unconventional measurement techniques such as the UHF range can be used to gain a trigger source for an acoustic measurement.

The described case studies show that both approaches can lead to a successful PD fault localisation, which is also facilitated with modern analysis tools such as visualisation of a 3D power transformer model.

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