

UHF AND ACOUSTIC PARTIAL DISCHARGE LOCALISATION IN POWER TRANSFORMERS

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Abstract: The reliability of electrical energy networks depends on the quality and availability of electrical equipment like power transformers. Local failures inside their insulation may lead to catastrophic breakdowns and can cause high outage and penalty costs. Beside the strength and type of a PD, the geometric PD position is of major interest concerning risk evaluation of the flaw. Conventional PD measurements according to IEC 60270 might show certain drawbacks during onsite and online measurements. The current work presents two so called unconventional methods, the electromagnetic PD measurement method, also known as the UHF-Method and acoustic measurements. The UHF-Method with a bandwidth from 300 MHz up to 3 GHz is based on the fact, that PD inside oil filled transformer emit electromagnetic waves measurable with oil valve sensors inside the transformer tank. Acoustic sensors from outside the tank measure in the ultrasonic frequency range the acoustic emissions of PD sources. For PD localization acoustic measurements are beneficially triggered with sensitive measurable PD signals like e.g. UHF signals, as demonstrated in the paper with the help of an onsite measurement on a large power transformer.

1 INTRODUCTION

Measurement of Partial discharges (PD) is a popular und established method for power transformers and gas-insulated switchgears insulation diagnosis. Furthermore localisation of PD sources is gaining importance for electrical equipment onsite as well as for manufacturers at commissioning tests. The knowledge of defect positions enables faster clearance of errors and thus lowering expenses for further diagnoses. That is especially valid for power transformers as one of the most important and expensive assets in energy market which will be considered in this contribution.

Several measurement techniques are available for PD detection. A first indicator for PD is often given by routine dissolved gas analysis (DGA)[1]. PD activity is indicated by increasing concentrations of its characteristic failure gases H₂ and CH₄. By measuring all dissolved gases DGA can only provide an integrated result. Considering all failures it delivers a trend of all PD in oil given by the changes of failure gas concentration.

For discrimination of PD sources electrical measurement according to IEC 60270 [2] is state of the art method. By measuring three phases respectively or simultaneously PD sources can be assigned to one specific phase. The type of PD fault is e.g. categorized using Phase Resolved PD patterns (PRPD) [3]. Cross talk effects between phases can be minimized by different approaches, e.g. star diagram method [4]. The so-called electrical method is sensitive towards external disturbance like corona, making onsite measurements demanding. Location of PD

sources geometry is limited to its phase, a detailed location described by 3-dimensional vectors is not possible.

Detailed localisation of PD sources can be achieved by using acoustic positioning methods. It is based on the propagation of acoustic waves originated by PD travelling through the transformer. Distributed acoustic sensors mounted at transformer tank's surface measure time of flight differences of acoustic PD signals allowing 3-dimensional positioning. In most cases at least 4 sensors are needed for positioning calculated with e.g. GPS-algorithm [5]. Like the electrical method, the acoustic measurement is affected by external disturbances. Depending on distance and strength, sound waves emitted by external corona discharges can be detected as well. High electric potentials and field strength may disturb sensors at onsite measurements.

Minimum sensitivity against external noise is provided by Ultra-High-Frequency method. PD emit electromagnetic waves at frequencies in GHz range which can be measured using UHF antennas inside transformer tanks [6]. Using the fast signal velocity UHF measurements can be used as real start time of a PD triggering acoustic measurement.

Challenges and advantages of the combination of UHF and acoustic measurements for PD localisation are discussed in this contribution.

2 MEASURING METHODS

2.1 Ultra-High-Frequency Measurement

That approach bases on the detection of electromagnetic waves emitted by PD inside an oil filled power transformer. Bandwidth reaches from 300 MHz up to 3 GHz (UHF-band: ultra high frequency band). The travelling speed of these waves in mineral oil ($\epsilon_r = 2.2$) is approximately $2.2 \cdot 10^8$ m/s. Measurements are realized using an UHF probe as can be seen in Figure 1.



Figure 1: UHF probe for power transformers

The UHF probe [7] was developed and designed at the Institute of Power Transmission and High Voltage Technology (IEH), University of Stuttgart. It is build to be installed on a power transformers' oil valve flange. It is oil tight and actually the installation at power transformer during full service is possible, because there is no galvanic contact with high voltage.

For PD localisation UHF-signals are used to trigger the acoustic sensors. This is possible because the probe only measures PD-events inside the power transformer. The transformer tank behaves like a faraday cage so no events from outside are detected. For example no corona discharges at the feeding overhead lines are measured [4].

A typical recorded UHF-PD-event is shown in Figure 2 and Figure 3. Figure 2 shows the fast raising signal in time domain with a signal raise time of approximately 500 ps.

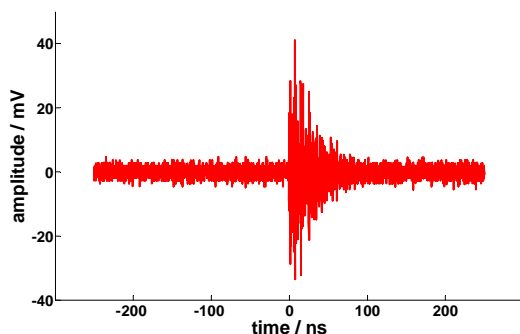


Figure 2: Typical UHF-PD-event in time domain

In Figure 3 the corresponding frequency spectra is shown. It contents broadband frequency portions up to 2.2 GHz.

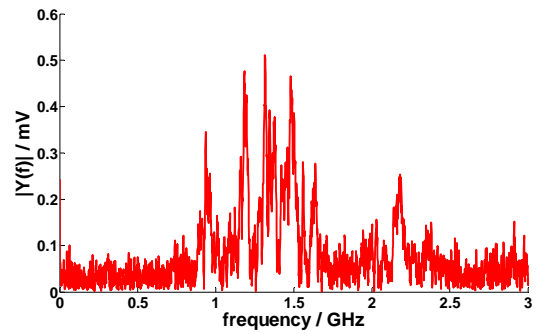


Figure 3: UHF-PD-event shown in corresponding frequency domain

PD-events can also be measured in reference to one phase of the transformers' feeding voltage. Aim is to get a phase resolved PD pattern to confirm that the measurable UHF signals correlate to PD by phase stable occurrence. The identification and characterisation of PD sources can be done similar to measurements according to IEC 60270.

An important difference to the IEC method is that there is no possibility to calibrate the UHF measuring method comparable to the calibration method of the electrical PD measurement according to IEC 60270 [8][9].

Summarising, the UHF method can be used for detection of internal PD and provide a trigger signal for acoustic PD localisation.

2.2 Acoustic Measurement

Acoustic localisation of PD is usually performed with acoustic sensors attached at the outside tank wall of transformers. A typical setup consists of a sensor and an attached amplifier. Both are shown in Figure 4. The advantages of acoustic measurement lie in its easy application and the quality of information it offers. Sensors can simply and quickly be attached at almost any position. Fixation is often performed with magnetic holders.

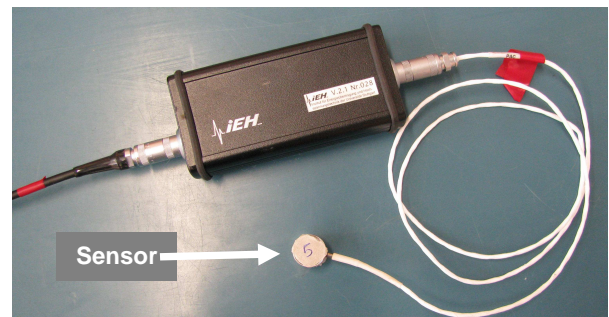


Figure 4: Acoustic sensor with pre-amplifier

If successful, the method returns a geometric position of PD within an acceptable error margin of few centimetres [5].

For acoustic measurement different time of flights are used to calculate PD locations. Acoustic waves emitted by PD are travelling through the transformer's oil. Depending on the internal structure like active part and windings signal propagation is attenuated. Reaching the transformer's tank signals couple into metal and its longitudinal component can be measured as acoustic wave at the tank wall outside.

Signal strength therefore strongly depends on the sensors' position in relation to the PD position. Generally, acoustic signal strength is low and may even be lower than noise level as shown in Figure 5, see first signal. In this case stand-alone acoustic measurement is not sufficient and a combination of UHF triggered acoustics is necessary to reduce noise by averaging.

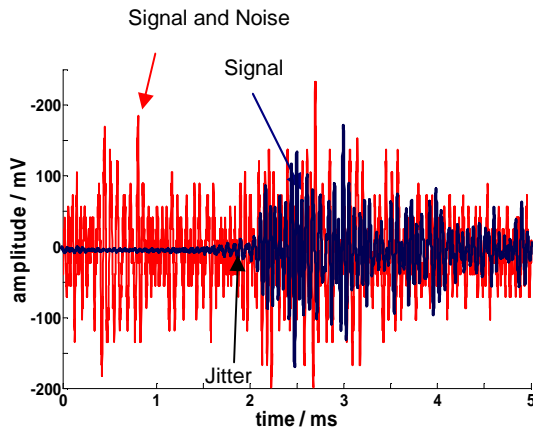


Figure 5: Averaged signal within Noise level

In any case the determination of the starting point of the measured signal is challenging. As Figure 5 shows, even with good signal to noise ratio jitter occurs at the beginning. As the signal shape may differ at different sensors, the signal starting point is not detectable by simple amplitude triggering. The use of methods including signal energy like Hinkley criterion [5] often leads to better results.

3 EVALUATION PROCESSES

3.1 Acoustic Localisation

PD also produces acoustic waves, which are measured with piezo-electric sensors installed at the outer tank wall. Their measurable frequency range is between 50 and 200 kHz. Due to comparatively high acoustic signal attenuation within the solid and liquid insulation material and structures inside the transformer sensitive acoustic measurements are hard to achieve [10]. 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 online 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 superimpose constructively whereas the white background noise is averaged to zero.

The process of PD localisation depends on the available and achievable information. Starting without any knowledge about a possible PD position, sensors are distributed all over the tank in search for any acoustic signals. Therefore relocation of sensors is a common but time-consuming need. If signals are found or already known by previous measurements (e.g. performed with electrical measurement according IEC) indicating a rough location, sensor can be arranged at promising positions at the tank wall.

For localisation approaches time delays between arriving signals are used to calculate the radius between sensor and source using known oil velocity v_{oil} of approximately 1400 m/s [5].

Figure 6 illustrates the geometric setup. The tank's simplified representation is a rectangle. The PD position is somewhere within the transformer. Its position is unknown.

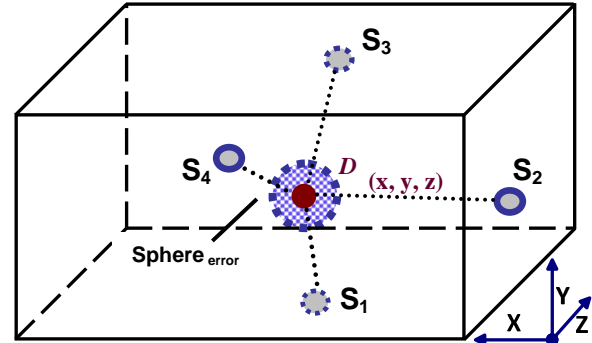


Figure 6: Acoustic measurement with 4 sensors

4 sensors are attached to the outside transformer. Origin of the coordinate system is defined as tank's lower right corner. Sensors measure time delays of PD by detecting relative time of arrival, as shown in Figure 7.

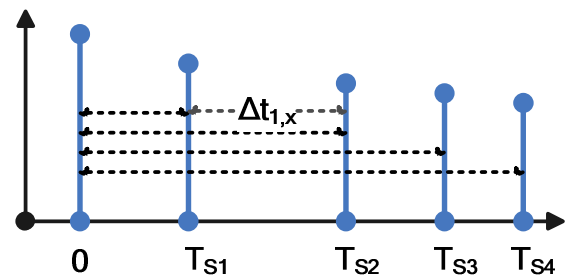


Figure 7: Acoustics time of flight to different sensors

Real start time of the PD is unknown and accordingly the time of flight T_{S1} to the first detecting sensor. Therefore the overall number of unknowns is 4 consisting of the 3 axis of the source vector and T_{S1} .

Hence, 4 time differences meaning 4 sensors are needed to form the required system of equations. $T_{S2,3,4}$ consist of the delta times $\Delta t_{1,x}$ and the unknown T_{S1} . Solving the system delivers the 3 dimensional vector of the source $PD_{source}(x, y, z)$.

$$\begin{aligned}(x - x_{s1})^2 + (y - y_{s1})^2 + (z - z_{s1})^2 &= (v_s \cdot T_{S1})^2 \\(x - x_{s2})^2 + (y - y_{s2})^2 + (z - z_{s2})^2 &= (v_s \cdot T_{S2})^2 \\(x - x_{s3})^2 + (y - y_{s3})^2 + (z - z_{s3})^2 &= (v_s \cdot T_{S3})^2 \\(x - x_{s4})^2 + (y - y_{s4})^2 + (z - z_{s4})^2 &= (v_s \cdot T_{S4})^2\end{aligned} \quad (1)$$

Accuracy depends mainly on the quality of signal detection, especially on determination of signal starting points. The PD can be expected within a sphere whose radius rises with measurement failure. Its center is defined by the source vector PD_{source} . In practise results with sphere radius $r=20\text{-}30\text{ cm}$ are sufficient because PD usually occur at typical structures like soldered lead exit, connections to bushings, etc. Correlation of the given source vector with typical issues indicates the actual source.

Furthermore, error radius can be minimized by improving time of flight measurement. Since signal starting point determination is difficult, its influence on time measurement can be reduced by using long delay times between sensors. Therefore distances between sensors should be as wide as possible paying regard to decreasing signal strength.

3.2 Combined UHF and Acoustic Measurement

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 PD 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 steel tank to the sensor without any reflections. Furthermore the localisation process has also to deal with acoustic waves travelling

faster through the tank wall than through the oil. The time of flights of the acoustic signals can be computed with the help of the Hinkley criterion [5]. It is based on the signal energy of the measured signal and results in an absolute minimum for the signal starting point.

4 ON-SITE MEASUREMENTS

4.1 General Setup

Considered is a 220kV / 50 MVA transformer. Voltage ($V = 1.7 V_{nominal}$) is applied using a three phase induced voltage test setup at 150 Hz. Oil temperature during measurement was 32°C, tap changer position is 14 which results in maximum rated primary voltage. Dimensions of the tank are $x = 6.12\text{ m}$, $y = 2.88\text{ m}$, $z = 2.30\text{ m}$, axis according to Figure 8.

Commercial electrical PD measurement equipment according to IEC 60270 is installed. Because of a missing possibility of triggering additional measuring equipment by the electrical measurements, UHF measurements are performed. Therefore one UHF probe is installed using a DN 125 flange with a DN 80 to DN 125 converter at the right side of the transformer as shown in Figure 8. The antenna of the UHF Probe extended 5 cm into the tank. UHF data are recorded by a storage oscilloscope at 3 GHz frequency range with 20 gigasamples per second (GS/s). A 10 m RG214 cable is used connecting probe and oscilloscope.

Acoustic signals are measured by piezoelectric acoustic sensors attached outside tank wall. Signals are recorded with a second storage oscilloscope triggered by UHF signals using external trigger setup. Measurements are performed with and without averaging.

4.2 Measurement Procedure

PD sources are localized with two different sensor setups. During the first setup the aim is to detect as many PD signals as possible. As shown in Figure 8 sensors are placed all over the tank surface to detect signals from the entire active part and thus from all detectable PD sources.

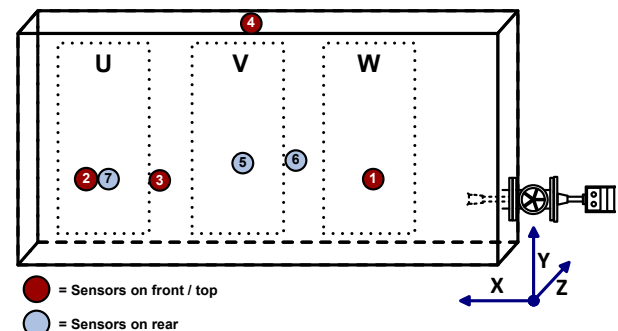


Figure 8: Sensor setup 1 for general PD search

After energisation of the transformer acoustic signals become measurable at all acoustic sensors. The starting points of all signals stay constant, that indicates only one active PD source inside the transformer. See exemplarily Figure 9 measurable signals of the sensors 1, 6, 4 and 2, measured without averaging and triggered by UHF signals.

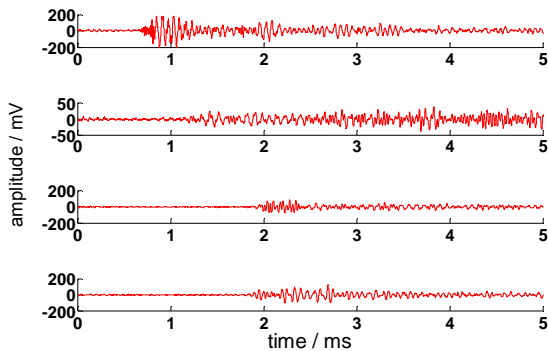


Figure 9: Signals of 4 acoustic sensors (from top to bottom sensor: 1, 6, 4, 2 of setup 1) with different start times, no averaging of signals

The emitted sound waves hit first sensor 1 with a time of flight less than one millisecond (ms). I.e. the PD source is located at roughly one meter distance to that specific sensor which indicates the PD to be located at phase W. That rough localization is used for the next sensor arrangement. First an investigation is performed, whether averaging of the acoustic signals is necessary in that case. With the same setup, by using averaging and UHF triggering, only signals correlated to the UHF emitting source are detected, whereas others superimpose destructively. Comparison of UHF triggered and non triggered signals show no differences, i.e. averaging is not necessary in that case. Calculated PD source locating vector is directed to the lower end of phase W, validating the electric PD measurement which also indicated a PD at phase W.

In setup 2 the sensor arrangement is concentrated on the estimated PD position. Considering good signal strength on the front, sensors could be distributed in the lower part of the transformer using increased distances of sensors for improved delay time measurement, see sensors 1, 2, 3 and 7 in Figure 10.

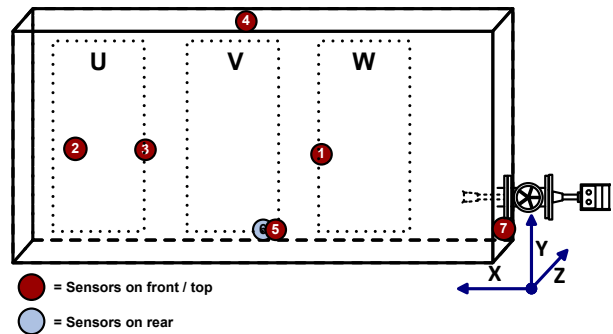


Figure 10: Sensor setup 2 with optimised sensor distribution for detailed localisation

Sensors 5 and 6 are positioned at the calculated x-vector of the source. Sensor 4 was not repositioned for reference. Using setup 2 the estimated PD localisation could be confirmed. The calculated source vector was pointed to the lower left end of phase W, see Figure 11.

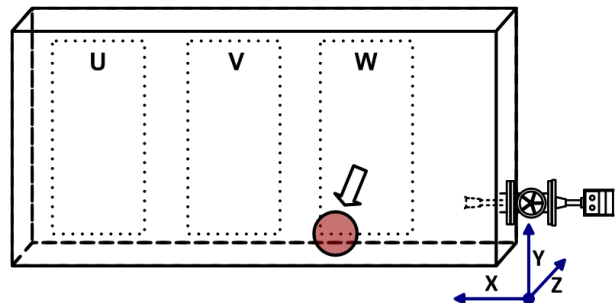


Figure 11: Calculated position of PD source

Assuming an error sphere with 30 cm radius, correlation with the active part design suggested two probable sources of PD: The lead exit or the first disk of phase W.

After the measurements the transformer was detanked and optically inspected. The lead exit was identified as the PD source and repaired. After that repairing the transformer passed the following acceptance test without any indication of PD activity.

5 CONCLUSION

PD measurements according to IEC 60270 are very sensitive for stand-alone PD measurements but may have the limit of not offering a trigger output channel. The UHF PD measurement method is usable as stand-alone measurement and as supporting measurement for off- and on-line PD detection especially for providing trigger events for further acoustic measurements. UHF sensors are easy to install and use. The sensitivity of unamplified UHF PD measurements is sufficient and is normally not affected by external disturbances.

Time of flights measured in the UHF range can be used for geometrical PD localisation. Additionally, measurements according IEC 60270 at all phases allow a localisation of the affected phase limb. 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. However, acoustic sensors are normally more sensitive to external disturbances than to 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. That influences partly can be eliminated with appropriate signal processing afterwards. Therefore, the compromise is a combination of methods, e.g. using sensitive low-frequency electric or UHF PD signals to provide triggering and by using averaging.

That combination was demonstrated and allowed a successful PD location, confirmed by a successful repair process.

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