Localization of PD Sources inside Transformers by Acoustic Sensor Array and UHF Measurements

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***Abstract*— Healthy power transformers are crucial components with regard to the reliability of electrical energy networks. Their insulation system condition is amongst others diagnosed with partial discharge (PD) testing. This PD testing needs to be done increasingly under on-site condition with correspondingly noise robust measurement technologies.**

Beside the strength and type of a PD the geometric PD position is of major interest concerning risk evaluation of the flaw. As presented in the paper, PD localization bases up to now mostly on time of flight differences of acoustic sensors which are spread geometrically around the transformer. Acoustic sensors can be sensitive to external disturbances or internal acoustic sources as e.g. core noise might cover PD signatures. Due to this acoustic measurements are beneficially triggered with sensitive measurable PD signals like e.g. UHF signals. For de-noising the acoustic signals averaging in time domain is performed. Averaging normally limits the localization feasibility to only one PD source.

The paper presents a new localization approach with the use of a planar uniform linear array of four acoustic sensors. The localization algorithms are explained and exemplary localizations are presented. Additionally, the presented new approaches of acoustic signal post-processing allow the localization of more than one PD source by statistical analysing.

Furthermore, time of flight differences between electromagnetical signals emitted by a PD is measurable. First investigations in laboratory are validated by localization of PD sources at transformers in field. The current work presents an example of PD localization on a transformer with the use of runtime differences measured in UHF range with 3 UHF sensors combined with time of flight information of 3 acoustic sensors.

Keywords -- Power transformer, partial discharge, PD, EC60270, UHF, Acoustic, PD localization, Acoustic Sensor Array

I. INTRODUCTION

The reliability of electrical power systems depends on the quality and availability of electrical equipment like power transformers. Examining existing insulation quality of oil/paper-insulated transformers during full operation or at least in the field gets more and more important because of the increasing number of transformers reaching their technical life expectancy. Local failures inside their insulation may lead to catastrophic breakdowns and might cause high outage and penalty costs. To prevent these destructive events power transformers are e.g. tested for partial discharges (PD) activity before commissioning and currently also during service.

Beside the strength and type of a PD the geometric PD position is of major interest concerning risk evaluation of the flaw. PD localization bases up to now mostly on time of flight differences of acoustic sensors which are spread geometrically around the transformer. The PD emitted acoustic waves 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 transformers, sensitive acoustic measurements are sometimes hard to achieve [1]. Additionally acoustic signals of PD might be covered by external or internal (core noise) mechanical noise. To increase the sensitivity of acoustic measurements it is combined with the sensitive UHF measuring method [2]. 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 (in time domain), the normally amplified acoustic PD pulses remain constructively overlapped whereas the white background noise is averaged to zero. Averaging normally limits the localization feasibility to one PD source, but the achievable accuracy lay with the range of centimeters [3].

Geometrical distances between sensors and the source of PD (calculated from the time of flights of the individual acoustic sensors) result in a spherical area inside the transformer. With at least three acoustic sensors and corresponding time of flights, it is possible to calculate the intersection of the spheres and thus to determine the PD location. It must be assumed that the acoustic waves travel directly in the line of sight from the PD source through the oil and through the steal tank to the sensor without any reflections. The time of flights of the acoustic signals can be computed objectively with the help of the Hinkley criterion [3]. It is based on the signal energy of the measured signal and results in an absolute minimum for the starting point of the signal.

Time of flights measured in the UHF range can be used for geometrical PD localization, too. The accuracy with e.g. two UHF sensors seems to be adequate to determine the phase where the PD is located or if the PD source might be at the tap changer [4]. However, since transformers rarely offer more than three UHF oil valves, an additional acoustic measurement method is usually required for localization. Using the knowledge gained from the UHF sensors, acoustic sensors can be placed near to the PD source at the transformer tank to speed up the localization process.

I. PD LOCALIZATION WITH ACOUSTIC SENSOR ARRAY

The localization approach base on an acoustic so called Uniform Linear Array (ULA), i.e. certain sensors are placed in a linear geometrical arrangement close together. In simplest case that are two sensors with the distance d at e.g. a transformer tank wall detecting internal acoustic waves, see Figure 1.

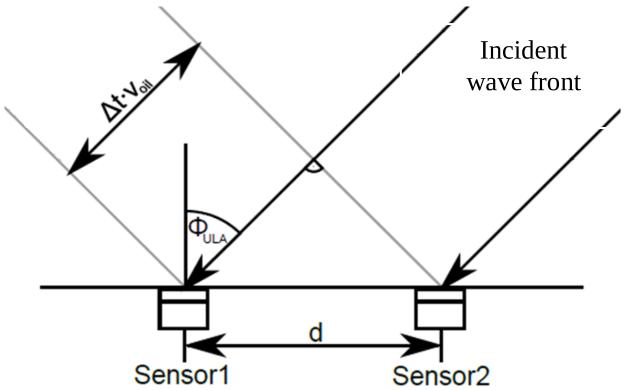

Figure 1. Two sensors measuring the time of flight differences of the same incident wave front

It shows two sensors positioned in a line and the incident acoustic wave front. On basis of the time of flight differences of the acoustic signals from the source of PD to the individual sensors the angle of incidence of a wave front on a sensor array can be determined. The angle Φ_{ULA} between the normal vector of the sensor level (orientated to the inside of the transformer) and the propagation direction of the incident wave is calculated with the parameters

- v_{oil} speed of acoustic wave in oil
- Δt time of flight difference
- d distance of sensors.

in accordance with

$$\Phi_{ULA} = \arcsin(\Delta t \times v_{oil} / d). \quad (1)$$

Whereas the distance d and the acoustic wave speed v_{oil} are well known, the time of flight differences between the sensors have to be measured and determined. Due to the small distance laying in the range of centimeters (here 11 cm) the time of flight differences lay in the range of hundreds of nanoseconds (ns). The Hinkley criteria, successfully used for geometrically spread acoustic sensors, can´t be used any more due to its inaccuracy in the range of microseconds (µs) [1]. Due to the necessity to determine the differences of the time of flights in the range of hundreds of nanoseconds, the cross-correlation of two signals is performed. Precondition is two similar signals, which is fulfilled due to the small distance between the sensors. The cross-correlation of two discrete signals f(n) and g(n) is defined by

$$(f * g)(n) = \sum_{m=-\infty}^{\infty} f[m] \cdot g[n+m] \quad (2)$$

and results in a folding of the signals. The maximum of the resulting sequence (f*g)(n) defines the necessary time shift of signal g(n) to achieve the maximum similarity in time domain to signal f(n). By this time shift the time of flight difference of the two acoustic signals is determined. Accuracy lay here in the range of the sampling rate, normally in the range of nanoseconds.

An additional advantage of the cross-correlation is the higher stability for time of flight determination in case of higher background noise and worse signal to noise ratios. In combination with a well designed filter of the acoustic signals, averaging of signals is not necessary any more and more than one PD source is detectable.

With the time of flight difference determined with the cross-correlation the angle Φ_{ULA} of the incident wave front can be calculated with equation (1). That angel describes not the explicit direction from where the waves are coming; it defines a cone like shown in figure 2.

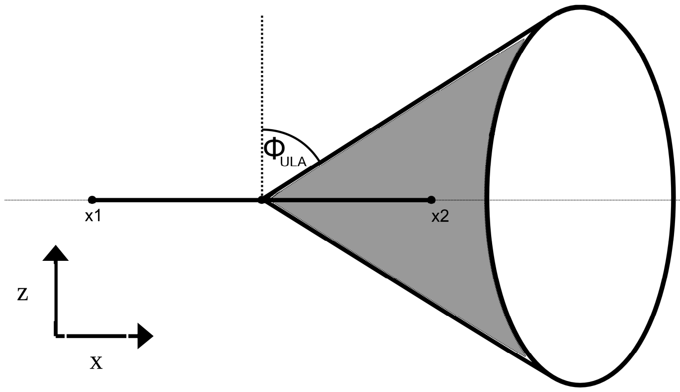

Figure 2. Resulting cone surface of possible origins of emitted acoustic waves

The sensors 1 and 2 are represented by the positions x1 and x2 on the x axis. The dotted line represents the normal vector of the array in the direction inside the transformer, here the z axis. The angle (90° - Φ_{ULA}) defines the opening angle of the correlating cone with it´s opening in x-direction. The possible PD source can be located anywhere on the surface of that cone, except for the half of the cone part which lay outside the tank.

By arranging two more sensors crosswise to the first ones, an ULA according Figure 3 is developed.

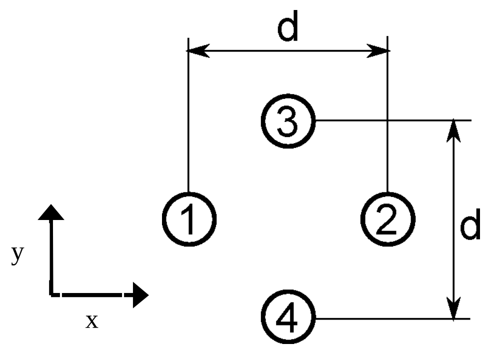

Figure 3. Defintion of sensors and axis with array, here d = 11 cm

Sensors 1 and 2 results in a cone as presented along the x axis, sensors 3 and 4 results in the same way in a cone along the y axis. The intersection of the cones results in a straight line representing the direction of the incoming acoustic waves from inside the transformer. The missing information for localization is than the distance r between the array and the PD source. It is calculated with the time of flight differences t_0 of the trigger signal (e.g. UHF signal) and the detected acoustic waves according

$$r = v_{oil} \times t_0. \quad (3)$$

The UHF measuring method is based on electromagnetic waves, which spread with approximately two-thirds of speed of light inside the transformer. Thus for localization 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.
The distance r in equation (3) results in a sphere around the ULA. Where the sphere is cutting the straight line of the determined direction by the ULA, the PD source is located, see Figure 4.

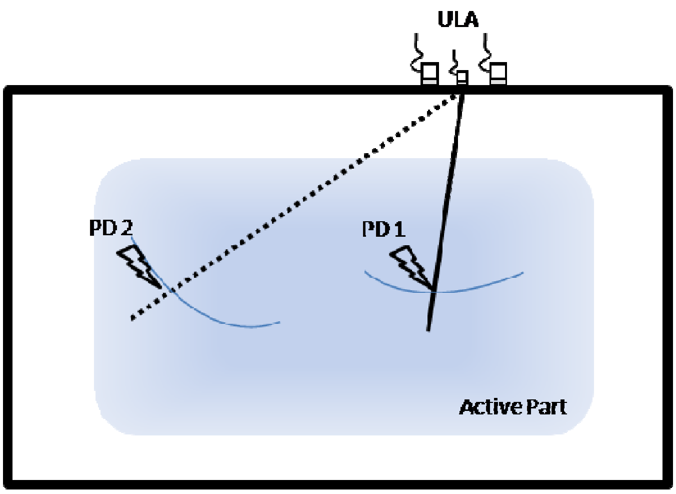

Figure 4. Topview – Principal of Acoustic ULA set-up with possible multi source localisation

As mentioned before, the cross-correlation is able to determine the needed time of flight differences also in case of higher background noise and averaging of acoustic signals for de-noising is not necessary any more. As shown in Figure 4 it is than possible and was successfully performed in laboratory, to localize more than one PD source within a transformer tank. Results of ongoing research on the right methods for statistical analyzing and clustering of different localization results will be presented in future.

II. Case Study on Acoustic Localization with Sensor Array

During an acceptance test inside a test facility a 320 MVA HVDC transformer was tested on PD. IEC60270 [5] measurements detected PD with an apparent charge of approx. 1500 pC. For localization purposes acoustic measurements were performed with averaged signals triggered by electrical PD signals measured acc. IEC. Localization basing on time of flight measurements with the corresponding localization algorithms [2] led to a PD position at the bottom of the transformer active part near to the tank wall; see top view of transformer in Figure 5.

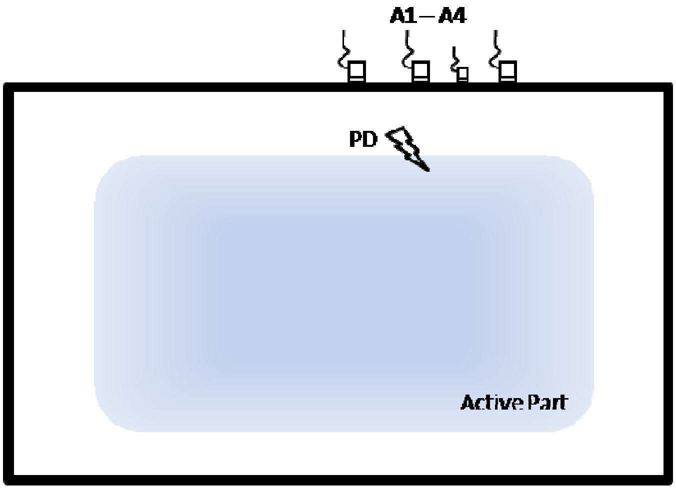

Figure 5. Topview - Acoustic set-up with localised PD at 320 MVA HVDC transformer

The acoustic sensors were located near the PD source and averaged acoustic signal was detectable with the use of the IEC conform trigger impulses. Other positions of the acoustic sensors didn't lead to measurable acoustic signals.
Due to experience the localization accuracy of that method isn´t high, because due to the small distance between the sensors (in the range of 50 cm) the resulting time of flights are very similar to each other and the intersection of the resulting spheres of each sensor become less sharp.
In that case of limited sensor positions with measurable acoustic signals the approach of the presented ULA was performed by rearranging the Sensors to an array as presented in Figure 3. The measured averaged acoustic signals of the 4 array sensors are presented in Figure 6.

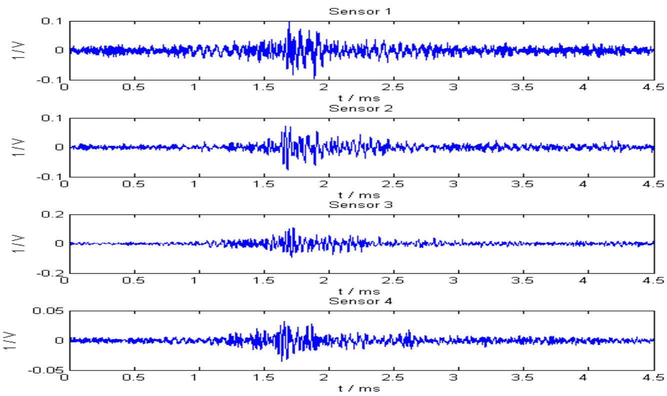

Figure 6. Measured acoustic signals of 4 sensors arranged as an ULA close to the estimated PD source

The signals of all sensors are quite similar to each other. The time of flight differences are in the range of hundreds of nanoseconds (ns) due to the small distances between the sensors. As presented, the time of flight determination bases on cross-correlation ($\Delta t_{1\text{-}2}$=850ns, $\Delta t_{3\text{-}4}$=36,85µs, t_0=1,5ms) and led to a localization result which confirmed the former found location with spatial deviation of 30 cm.

A comparison of both methods to determine the accuracy is missing because the transformer has to be detanked first for optical inspection and repair process.

III. CASE STUDY UHF & ACOUSTIC LOCALIZATION

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 [5] at sub 1 MHz frequencies. Consequently, UHF PD measurements for PD detection in combination with acoustic measurements for PD localization were performed in order to get reliable results.

In this case the transformer possessed three oil filling valves and three identical UHF Sensors were installed. Figure 6 shows the positions of the UHF probes (UHF 1 – UHF 3). 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.

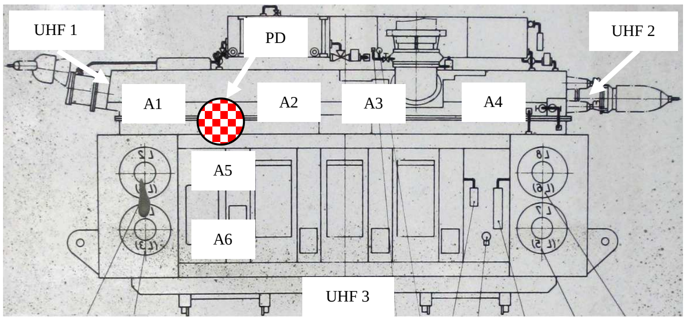

Figure 7. Located PD source with position of UHF Probes (UHF 1-3) and Acoustic Sensors (A1-A6)

At nominal voltage, UHF signals from internal sources were detectable with all three probes. In Figure 8 the exemplarily measured signals of the UHF (UHF 1 and 2) probes are shown, measured without amplification.

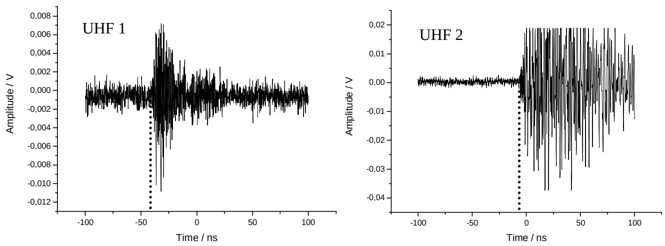

Figure 8. Measured time of flight differences between UHF sensors 1 and 2, here approx. 45 ns

Recognizable are time of flight differences in the range of nano seconds (ns) between the signals, here approx. 40ns. Taking time of flight differences caused by different lengths of measuring lines into account, a first estimation of the geometric PD location led to the tap changer. Due to that information six acoustic sensors (A1 – A6) are placed on the tank as presented in Figure 7.

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

After transportation of the transformer to the manufacturer the localization result was proofed by an IEC triggered acoustic measurement in the test field and the transformer was detanked. The optical inspection of the active parts at the tap changer confirmed the localization results.

After repair procedure the transformer passed the acceptance test without any indication of PD activity and was put back into service.

IV. CONCLUSION

The presented approach of PD localization by array arrangement of acoustic sensors is feasible. In case of limited sensor positions with measurable acoustic signals, the accuracy due to cross-correlation time of flight determination increase compared to time of flight determination by energy-based Hinkley criteria. Furthermore the presented statistical signal processing method allows the localization of more than one PD source.

UHF signals are workable for basic localization and accuracy in the range of half a meter. This information allows an optimization of the position of acoustic sensors near to the estimated PD source location.

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