New robust non-iterative algorithms for acoustic PD-localization in oil/paper-insulated transformers

Sacha M. Markalous, Stefan Tenbohlen, Kurt Feser
University of Stuttgart, IEH, Pfaffenwaldring 47, D-70569 Stuttgart
E-Mail: sacha.markalous@ieh.uni-stuttgart.de

Abstract: The diagnostic examination of partial discharges (PD) for the condition assessment of insulating systems of transformers according to the IEC60270 standard is normally carried out in test bays to control new products after a manufacturing process. An increasing demand for assessing the insulating quality of aged equipment which is met by means of onsite or online PD measurements is noticed. Online/onsite acoustic PD measurements of oil-paper insulated transformers could be grouped into two major tasks. First is to provide evidence of PD (detection) as sensitive as possible. Second is the in many respects important determination of the failure location (localization of the PD).

Depending on whether mixed-acoustic (i.e. electric or electromagnetic triggering) or all-acoustic (acoustic triggering) measurements are used three different approaches for the system of nonlinear observation equations with three (space coordinates (x, y, z) of the PD) or four unknowns (an additionally unknown temporal origin) are presented and discussed. The new approach within the acoustic signal processing which works with pseudo-times allows for utilization of robust direct GPS (Global Positioning System) solvers instead of the previously used iterative algorithms. Laboratory experiments as well as onsite/online measurements given in the contribution show the advantages of the new positioning algorithms.

INTRODUCTION

Gathering information about the insulation characteristics of installed power transformers in service is an important task nowadays. These information form the basis for conditioned based maintenance strategies and support continuous risk assessment. Beside well-known dissolved gas in oil analysis PD measurements represent a powerful and approved diagnostic tool to evaluate current insulation conditions of transformers. Recently partial discharge (PD) diagnosis have been used onsite/online.

In addition to sensitive PD detection and possibly recognition of its nature the PD location is of great interest. Since PD act as source of acoustic (i.e. mechanical) and electromagnetic waves arrival times of these signals especially the acoustic ones can be used for a three dimensional localization. An online PD positioning helps to plan maintenance or repair actions cost and time efficiently. Due to inevitable measuring errors or sensitivity limits in the acoustic signals and the corresponding arrival times robust algorithms calculating PD positions are needed. A general overview of alternatives of acoustic spatial PD localization (all-acoustic and mixed-acoustic) giving the mathematical description of the problem is given at the beginning. Subsequently a laboratory case study of acoustic PD positioning with triggering on an electromagnetic PD signal is discussed. One possibility of automated and objective arrival time determination with a signal-energy based criteria is introduced and localization results using iterative and new direct solvers are compared. Finally an application of all-acoustic onsite/online PD measurements on a 200 MVA, 380/220kV single-phase transformer is presented.

SPATIAL PD LOCALIZATION ON THE BASIS OF SPHERE FUNCTIONS

For localizations two main approaches can be found. On the one hand alterations of the signal amplitude or deformations of the signals shape along the propagation path can give hints for a source location. On the other hand measured arrival times are used to calculate the origin of signals. In the following only the second alternative is analyzed.

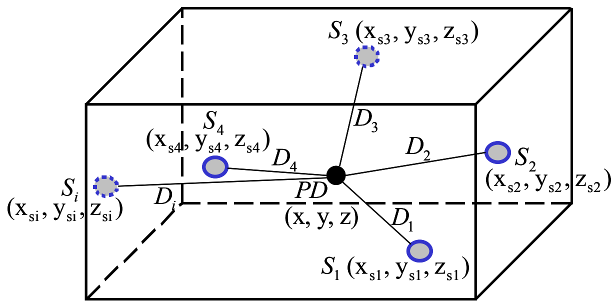

Fig. 1: Acoustic sensors on a transformer tank with a PD inside using Cartesian coordinates

Figure 1 shows a schematic view of a transformer tank with i attached acoustic sensors, PD inside and the resulting distances D_i from the sensors S_i to the PD origin. Such arrangements are the geometric basis for the following mathematical formulations. The PD event is thus modeled as a point source radiating an acoustic wave in a homogenous medium (here oil). The appropriate nonlinear observation equations are in the simplest case characterized by sphere functions which intersect at the PD origin. Depending on whether mixed-acoustic (i.e. triggering with the electric or electromagnetic PD signal) or all-acoustic (acoustic triggering) measurements are used the number of unknowns is three (space coordinates (x, y, z) of the PD) or four (an additionally unknown temporal origin) respectively. Hence an exact spatial localization of the PD origin needs in the determined case at least three or four acoustic sensor signals.

Absolute Time Approach

For mixed acoustic measurements i.e. an usage of an electric or electromagnetic triggering the instant the PD occurs is known. Mathematically this correspond to an absolute time measurement which is illustrated in Figure 2.

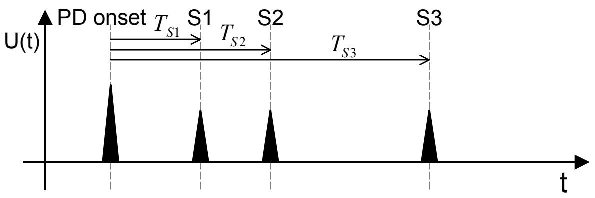

Fig. 2: Schematic visualization of acoustic arrival times in reference to the known PD onset (electric/electromagnetic PD trigger signal)

The associated sphere functions with the three unknown PD coordinates in space (x, y, z), the measured arrival times T_{Si}, the assumed sound velocity v_s and the cartesian sensor coordinates (x_{si}, y_{si}, z_{si}) have the following appearance

$$(x-x_{s1})^2+(y-y_{s1})^2+(z-z_{s1})^2=(v_s\cdot T_{S1})^2 \quad \text{(1a)},$$

$$(x-x_{s2})^2+(y-y_{s2})^2+(z-z_{s2})^2=(v_s\cdot T_{S2})^2 \quad \text{(1b)},$$

$$(x-x_{s3})^2+(y-y_{s3})^2+(z-z_{s3})^2=(v_s\cdot T_{S3})^2 \quad \text{(1c)}.$$

These are functions describing spheres with radii D_i which are defined with

$$D_i^2=(v_s\cdot T_{Si})^2 \quad \text{(2a)}.$$

The approximation of a vanishing propagation delay of e.g. the electromagnetic PD signal (nanosecond range) is valid because the acoustic signals show typical delay times in the range of micro- up to millisecond range.

Time-Differences Approach

Using all-acoustic measurements stands for an acoustic triggering of the acoustic channels. The exact instant the PD occurs is hence unknown which results in the need of one more sensor signal.

In the time-difference approach the acoustic wave reaches the nearest sensor first (assuming straight propagation) and triggers the recording process on all sensors simultaneously. Having e.g. four sensors - which is a not over-determined case - gives three time-differences starting from the first-hit reference sensor. This is illustrated in Figure 3, which shows time-differences of four acoustic signals in reference to the unknown PD onset.

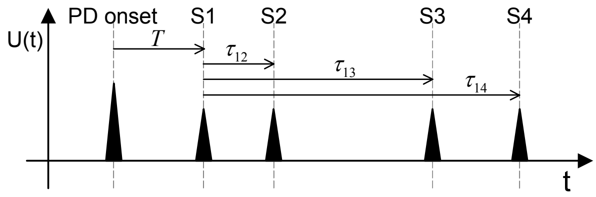

Fig. 3: Schematic visualization of acoustic time-differences in reference to the unknown PD onset

Just the radii (right hand sides) of the sphere functions are modified with the additional unknown time origin T and the measured time-differences τ_{1i}. The non-linear observation equations of the time-differences approach are as follows:

$$(x-x_{s1})^2+(y-y_{s1})^2+(z-z_{s1})^2=(v_s\cdot T)^2 \quad \text{(3a)},$$

$$(x-x_{s2})^2+(y-y_{s2})^2+(z-z_{s2})^2=(v_s\cdot(T+\tau_{12}))^2 \quad \text{(3b)},$$

$$(x-x_{s3})^2+(y-y_{s3})^2+(z-z_{s3})^2=(v_s\cdot(T+\tau_{13}))^2 \quad \text{(3c)},$$

$$(x-x_{s4})^2+(y-y_{s4})^2+(z-z_{s4})^2=(v_s\cdot(T+\tau_{14}))^2 \quad \text{(3d)}.$$

Pseudo-Time Approach

A second and within the acoustic signal processing new alternative of stating the system of non-linear observation equations for all-acoustic measurements works with pseudo-times T'_{Si} (traveling times with additional constant time-offset). This results in a GPS (Global Positioning System) mode of the formulas. In this case the accessory unknown is a "receiver" time offset Δt. Figure 4 depicts how the pseudo-times of four acoustic signals are connected to the unknown PD onset.

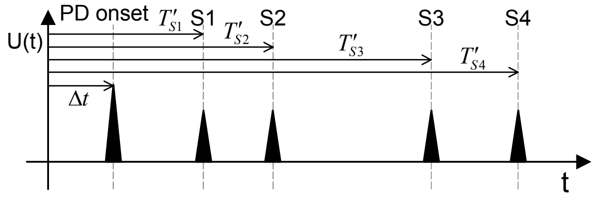

Fig. 4: Schematic visualization of acoustic pseudo-times in reference to the unknown PD onset

All-acoustic measurements with four or more sensors act like an "inverse" satellite-receiver positioning problem and result in mathematically identical formulas. A rather familiar way of handling pseudo-times is doing measurements with pre-triggering. Here the time origin depends on the adjusted pre-trigger level.

Again just the radii of the sphere functions are modified with the additional unknown Δt. With no system over-determination one gets:

$$(x-x_{s1})^2+(y-y_{s1})^2+(z-z_{s1})^2=(v_s\cdot(T'_{S1}-\Delta t))^2 \quad (4a),$$

$$(x-x_{s2})^2+(y-y_{s2})^2+(z-z_{s2})^2=(v_s\cdot(T'_{S2}-\Delta t))^2 \quad (4b),$$

$$(x-x_{s3})^2+(y-y_{s3})^2+(z-z_{s3})^2=(v_s\cdot(T'_{S3}-\Delta t))^2 \quad (4c),$$

$$(x-x_{s4})^2+(y-y_{s4})^2+(z-z_{s4})^2=(v_s\cdot(T'_{S4}-\Delta t))^2 \quad (4d).$$

The observation equations (4a-d) become symmetric due to the fact that the unknown time offset Δt is contained in all pseudo-times T_{Si}. With the relation

$$T'_{S1}-\Delta t=T \quad (5)$$

a second step calculation yields the instant the PD occurs. Furthermore the two variants of the system of equations for all-acoustic measurements are interconnected through equation (5).

The pseudo-time notation turned out to be very universal for acoustic source location since it even allows to localize defects with (absolute) time information from mixed-acoustic measurements. In terms of pseudo-times this is the special case of a vanishing time offset Δt. Other fields of mechanical location problems can also be handled [7].

Algorithmic Solution Strategies

Non-linear equation systems (like e.g. (4a-d)) are commonly solved with iterative algorithms. One great drawback of these solvers is the sometimes strong dependency on the initial value which must be provided from the user. The solutions of all the presented equation systems could be computed iteratively. Nevertheless a great advantage of the pseudo-time notation is a utilization of direct solution strategies available for GPS-problems. They exist for the determined and also for the over-determined case [1], [2], [5], [6]. With the use of direct algorithms one gets rid of the initial value dependency and furthermore it will be shown below that direct solvers generate more stable positioning results in the presence of inevitable measurement errors in the arrival times.

LABORATORY CASE STUDY OF ACOUSTIC PD POSITIONING

An oil-immersed high voltage winding in a transformer housing serves as a case study where general dependencies of positioning results on errors in arrival times, errors in assumed velocity and different solver strategies (iterative and over-determination direct solver [2] for pseudo-time equations) are analyzed.

Fig. 5: Transformer tank with high voltage winding, PD stimulated at the inner of the winding at (0.71 /0.225 / 0.875) m in cartesian coordinates

The housing dimensions are 1.77m in x-direction (length), 0.77m in y- direction (width) and 1.56m in z-direction (height) and it is situated in a high voltage laboratory as pictured in Figure 5.

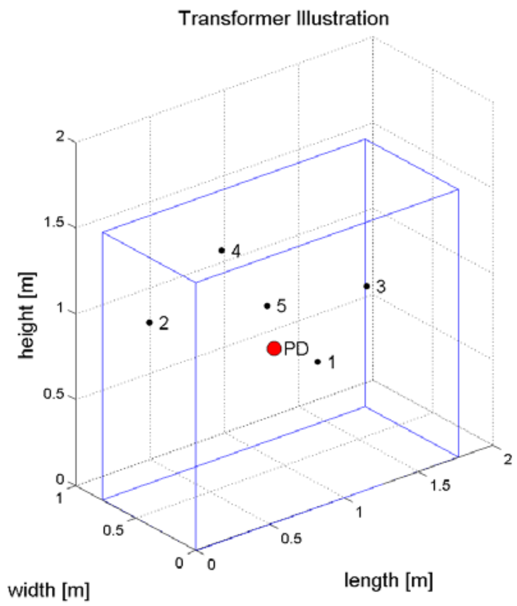

Fig. 6: Spatial illustration of the arrangement of acoustic sensors on the housing and the PD inside

PD (electric level about 488 pC) at the inner side of the winding was stimulated with an electrode on ground. High signal/noise-ratios of the time signals were featured, so much smaller levels could have been resolved. The oil temperature in the tank was 21°C with an appropriate sound velocity v_s of about 1417 m/s used for the calculations [4]. The acoustic channels were triggered with an sensitive electromagnetic PD signal (UHF range), so this is the special case of a time offset $\Delta t = 0$. Figure 6 shows a spatial illustration of the whole arrangement of five acoustic sensors on the housing and the PD inside, while Figure 7 illustrates the front view, side view and top view of the arrangement. E.g. sensor 3 is not located directly above the PD hence it features due to its position relative to the PD a large part of steel in his propagation path. Compared to the other sensors this is the worst position for detecting acoustic signals.

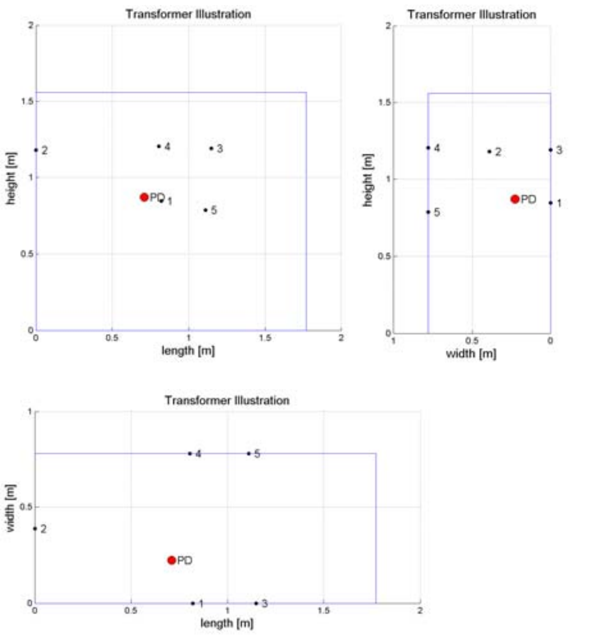

Fig. 7: Front view (up left), side view (up right) and top view (bottom) of the arrangement

Arrival time determination

A correct objective arrival time determination is an important part of the localization procedure. Good experiences have been gathered with a statistic signal-energy based criteria [3]. The energy curve of the signal is here defined as

$$S_i = \sum_{k=0}^{i} x_k^2 \qquad (6).$$

The separation of the signal from the noise part and the realization of the criteria is managed with the difference

$$S_i' = S_i - i\delta = \sum_{k=0}^{i} x_k^2 - i\delta \qquad (7)$$

where a trend δ is subtracted and which generates a partial energy curve. The trend is dependent on the signal energy of the whole signal S_N and the sample number N. It is determined by

$$\delta = S_N / N \qquad (8).$$

The calculated partial energy curve possesses a minimum which corresponds, so the correct assumption, with the signals arrival time (see Figure 8).

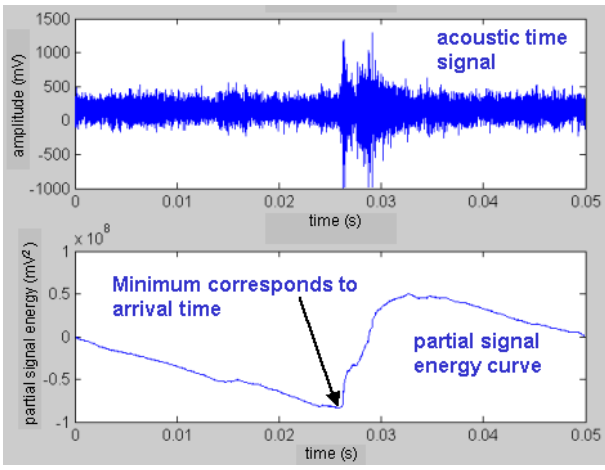

Fig. 8: Acoustic signal (top) with its partial signal energy curve (bottom) exhibiting a minimum

The energy criteria is applied globally for all 5 sensors. This stands for searching through the whole signal as shown in Figure 8 even if there is more than one impulse visible e.g. due to reflections or a decomposition of the first wave into steel-propagated and oil-propagated wave.

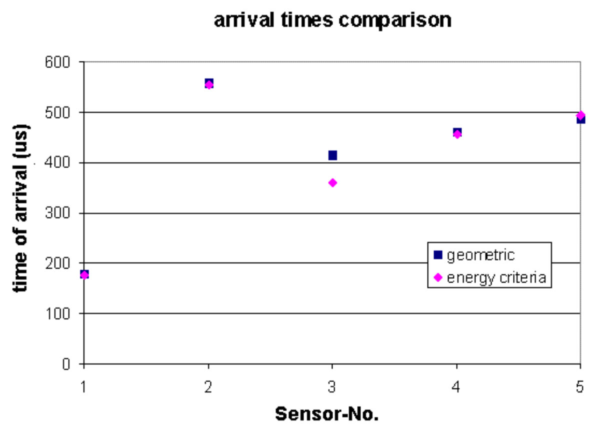

Fig. 9: Comparison of the geometric arrival times and the measured arrival time processed with the energy criteria

In the laboratory case one exactly knows where the PD is located and thus can calculate geometric arrival times meaning analytically determined reference times. In Figure 9 these geometric arrival times are compared to those automatically acquired with the energy criteria processing the measured acoustic signals.

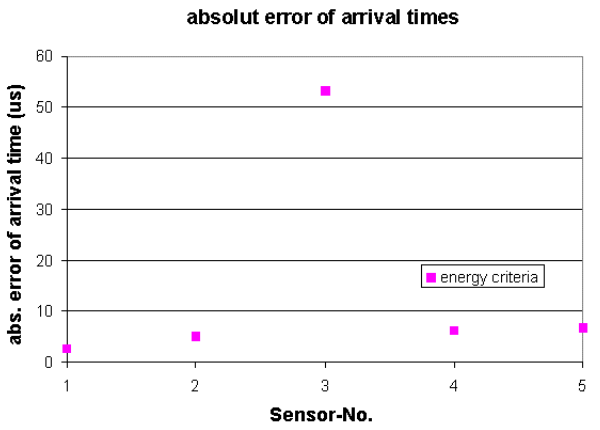

Fig. 10: Absolute error of the measured arrival times processed with the energy criteria

Sensor 3 shows a significantly higher error in the automatically determined arrival time (see Figure 9/10/11) which is mainly caused by its large part of steel in his propagation path. The higher sound velocity in steel (about 3200 m/s for the transversal wave) results in an earlier arrival of the acoustic wave traveled via steel. With knowledge of the propagation physics one is able to preselect that part of the acoustic signal which represents the wave traveled on the direct way in oil. Doing so for sensor 3 results in a reduced relative error of its arrival time of 3.96 percent.

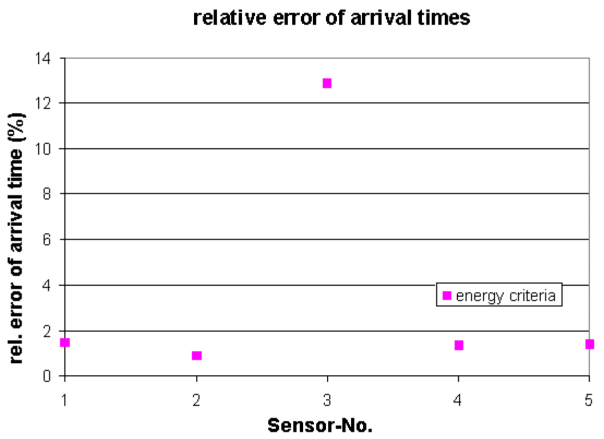

Fig. 11: Relative error of the measured arrival times processed with the energy criteria

Localization accuracy

Through a continuous comparison of positioning results of the iterative and over-determination direct solver [2] for pseudo-time equations general location accuracy dependencies are analyzed in two steps. First only the four sensor signal (1, 2, 4, 5) with arrival time errors below 2% are examined (determined case). Second the temporal highly deviating sensor 3 is added in the analysis (over-determined case).

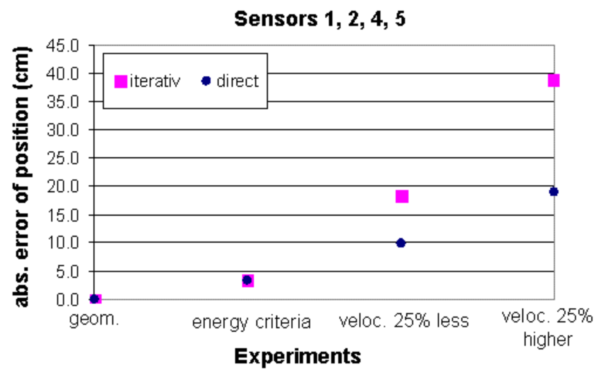

Fig. 12: Absolute error of position for different experiments (determined case and exact or reasonable arrival times)

Figure 12 shows the absolute error of position for the use of geometric arrival times, energy criteria processed times and wrong assumed propagation velocities. The percentage reduction and increase respectively refers to the appropriate sound velocity v_s (about 1417 m/s) of 21°C. While location results for exact (no error) or not excessively incorrect arrival times (3.4 cm error) are comparable and satisfying the direct solver generates more stable results for wrongly assumed propagation velocities.

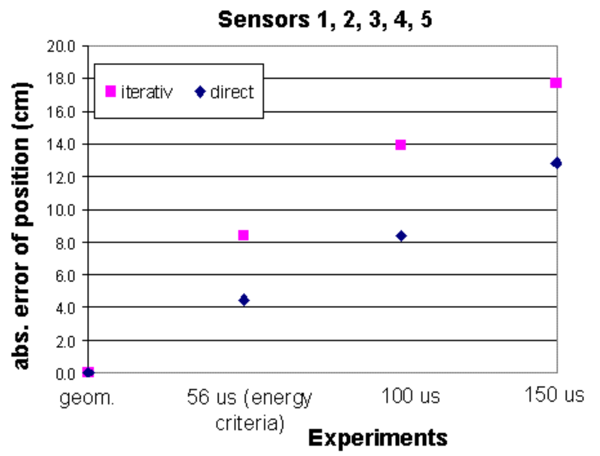

Fig. 13: Absolute error of position for different stages of error in the arrival time of one sensor (sensor 3)

In Figure 13 the absolute errors of position with the additional use of sensor 3 are illustrated. The sound velocity for the calculations in these experiments was constantly defined by the sound velocity in oil at temperature of 21°C. While 56 us absolute error (relative 12.86 %) in the arrival time of sensor 3 result in an absolute location error increase of about 1.1 cm to 4.5 cm for the direct solver, the iterative solver yields 8.4 cm absolute error. If higher temporal absolute errors for sensor 3 are simulated (100 us and 150 us) again more stable results are provided from the direct solver.

APPLICATION ON POWER TRANSFORMERS: ALL-ACOUSTIC ONSITE/ONLINE PD LOCALIZATION IN A 200MVA, 380/220KV-SINGLE-PHASE TRANSFORMER

Over a period of several months onsite all-acoustic measurements were performed at a 200 MVA single-phase transformer whose gas-in-oil diagnosis indicated PD. During an offline applied voltage test an electric PD measurement revealed PD levels up to 600 pC and an autonomous acoustic measurement recorded an impulse on four sensors simultaneously [8]. The oil-temperature was about 26 C (which corresponds to 1387m/s sound velocity in oil) according to information from the operating company. Figure 13 pictures the top view of the housing of the transformer with the sensor positions and the average of the calculated position calculated PD location.

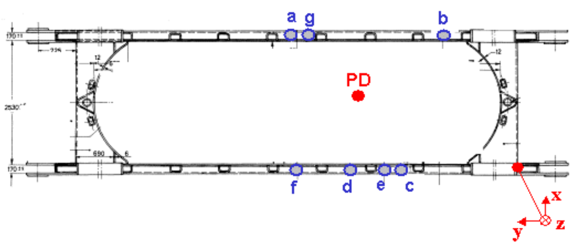

Fig. 13: Top view of the housing of the 200 MVA transformer with attached acoustic sensors and the calculated PD location inside

In table 1 location result are summarized. The result of "measurement 1" was determined iteratively because the direct solver generated a complex solution due to strongly erroneous time information. For the remaining two measurements the direct solver was used.

calculated PD-origin	x [m]	y [m]	z [m]
measurement 1 (offline a, b, c, d)	1.40	3.12	2.27
measurement 2 (online c, d, e, f, g)	1.25	3.19	2.23
measurement 3 (online a, c, d, e, f, g)	1.27	3.22	2.19

Tab. 1: Acoustic PD measurements over a period of several months with changing sensor positions

CONCLUSION

At the beginning the mathematical description of acoustic spatial PD localization (all-acoustic and mixed-acoustic case) were discussed. The new pseudo-time approach and its utilization of direct solution strategies available for GPS-problems was introduced. Using a laboratory case study of acoustic PD positioning with triggering on an electromagnetic PD signal general positioning dependencies where analyzed. Regarding automated and objective arrival time determination a signal-energy based criteria and its accuracy compared to analytical arrival times were presented. Arising localization results using an iterative and a direct solver were compared whereas more stable results were featured by the direct solver. Finally an application of all-acoustic onsite/online PD measurements on a 200 MVA, 380/220kV single-phase transformer was presented.

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