ALL-ACOUSTIC PD MEASUREMENTS OF OIL/PAPER-INSULATED TRANSFORMERS FOR PD-LOCALIZATION

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Dealing with all-acoustic online PD measurements of oil/paper-insulated transformers one encounters two main tasks. First is detection of a PD and its distinction from impulse-shaped acoustic disturbances in terms of a monitoring decision "PD-yes/no". Second is the localization of the PD which is needed e.g. for risk assessment. There one has to give the acoustic amplitude a relation to the electrical amplitude and get an appropriate Picocoulomb (pC) value for considerations concerning deterioration. In case of doing computations with traveling times an exact all-acoustic geometric localization of the PD origin needs at least four sensor signals. Two variants for the system of non-linear observation equations with four unknowns can be distinguished. Working with time-differences starting from a first-hit reference sensor gives three unknown coordinates in space and an unknown time origin. Another approach presented is stating the system of equations in a GPS (Global Positioning System) form handling pseudo-times. In this case three coordinates and a receiver time offset constitute the unknowns.

Key words – Acoustic PD measurements, online PD localization, non-linear observation equations, time-differences, pseudo-time approach, iterative solver algorithms, direct solution strategies

1 INTRODUCTION

Permanent monitoring of high voltage devices should allow conditioned based maintenance strategies and serve asset appraisements. Large power transformers reaching their nominal life-time additionally need some sort of continuous risk assessment to avoid high consequential costs in case of a total breakdown. For these purposes reliable and approved partial discharge (PD) diagnosis have been used online recently.

Different PD measuring techniques are using different physical peculiarities of the PD phenomenon e.g. electric currents (according to IEC 60270), gas formation (dissolved gas in oil analysis), electro-magnetic (UHF-range) or acoustic radiation for online measurements. In general two information are necessary regarding the PD – its level and its location. Having information of the PD origin is essential to assess e.g. the risk potential of the fault. It would also be appreciated to know about the PD origin without any complex offline localization to plan and start maintenance / repair actions cost or time efficiently. Another point regarding acoustically recorded PD signals is that one needs to have the PD origin if a corresponding electric level should be estimated [4].

Concerning the geometric localization of the PD origin not all methods noted are suitable for the PD localization which is as mentioned important in many respects. The acoustic method has some outstanding properties for this task which are shortly reported at the beginning of the paper. A rather algorithmic approach to all-acoustic spatial PD localizations giving the mathematical description of the problem and possible solution alternatives is following. Three sample localization finally show possibilities and limits of all-acoustic PD localization.

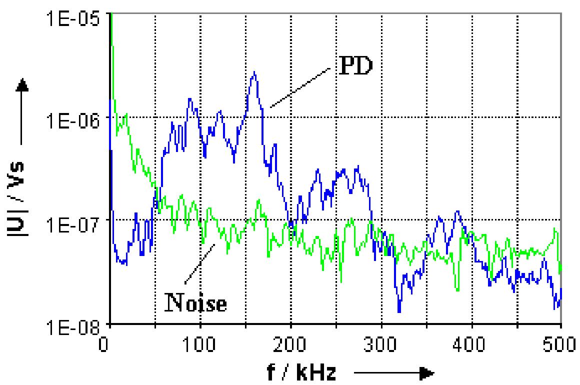

Figure 1: Frequency spectra of acoustic measurements using piezoelectric sensors [3]: disturbances (0...50 kHz) and PD (50...200 kHz)

2 ASPECTS OF ONLINE ACOUSTIC PD MEASUREMENTS

2.1 ACOUSTIC ONLINE NOISE ENVIRONMENT

Contrary to the electric PD measurement method (IEC 60270) which is strongly influenced by corona the acoustic noise environment on site is of good nature. Corona is acoustically not disturbing for reasons of measuring principle. Even though mechanical disturbances like magnetostriction or external loose parts have an measurable influence, environmental “noises” as hail, sand, etc. do not have that high spectral components as a PD has. This is shown in Figure 1 which demonstrates how the “noise” and PD spectra act up to a frequency of 500 kHz.

2.2 HARDWARE AND SENSORS

Advantageous in practice of the acoustic detection is the application of the in most cases used piezoelectric sensors which provide a wideband conversion of incoming mechanical pressure waves (emitted from the PD) in electrical signals meeting signal classification needs.

The piezoelectric sensors are conveniently mounted on the outside of the tank wall. A thin layer of beeswax could do the acoustic impedance matching between the ceramic sensors and the steel tank wall to minimize losses of this junction [8]. This nondestructive outer application of the measuring system can be managed while the transformer stays in full service because there is no electrical connection needed to high voltage circuit.

3 MATHEMATICAL DESCRIPTIONS OF ALL-ACOUSTIC SPATIAL PD LOCALIZATION

Two main methods for a localization can be found. On the one hand alterations of the signal amplitude or deformations of the signals shape can give hints for a source location. On the other hand measured traveling times could help to calculate the origin of signals. This work only deals with the second alternative and describes two variants to do computations with all-acoustic traveling times.

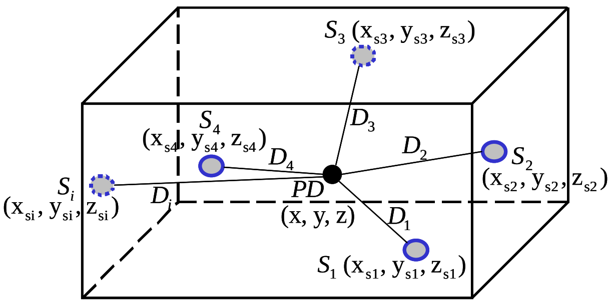

Figure 2: Acoustic sensors on a transformer tank with a PD inside using Cartesian coordinates

Figure 2 shows a schematic view of a transformer tank with i attached acoustic sensors, a 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 emitting an acoustic signal whose time origin is unknown.

Summarizing that means for computations with all-acoustic traveling times an exact spatial localization of the PD origin needs at least four sensor signals. The space coordinates of the PD are unknown and depending on the variant of the system of non-linear observation equations additionally one time value.

3.1 TIME-DIFFERENCES APPROACH

The acoustic wave reaches the nearest sensor first (assuming straight propagation) and triggers a 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 event signal “electric”.

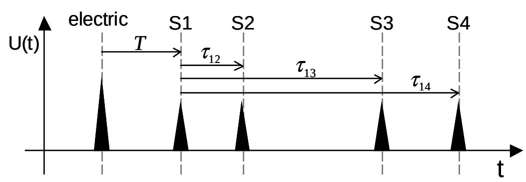

Figure 3: Schematic visualization of acoustic time-differences in reference to the (unknown) electric PD signal

Three unknown coordinates in space, the unknown time origin T, the time-differences τ_{1i}, the sound velocity v_s and the Cartesian sensor coordinates (x_{si}, y_{si}, z_{si}) constitute the non-linear observation equations of the time-differences approach:

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

$$(x - x_{s2})^2 + (y - y_{s2})^2 + (z - z_{s2})^2 = (v_s \cdot (T + \tau_{12}))^2 \quad \text{(1b),}$$

$$(x - x_{s3})^2 + (y - y_{s3})^2 + (z - z_{s3})^2 = (v_s \cdot (T + \tau_{13}))^2 \quad \text{(1c),}$$

$$(x - x_{s4})^2 + (y - y_{s4})^2 + (z - z_{s4})^2 = (v_s \cdot (T + \tau_{14}))^2 \quad \text{(1d).}$$

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

$$D_1^2 = (v_s \cdot T)^2 \quad \text{(2a),}$$

$$D_i^2 = (v_s \cdot (T + \tau_{1i}))^2 \quad \text{(2b).}$$

3.2 PSEUDO-TIME APPROACH

Stating the system of non-linear observation equations with pseudo-times T_{Si} (traveling times with additional constant time-offset) results in a GPS (Global Positioning System) form. In this case three coordinates and a "receiver" time offset Δt constitute the four unknowns. Figure 4 depicts how the pseudo-times of four acoustic signals are connected to the (unknown) PD event signal "electric".

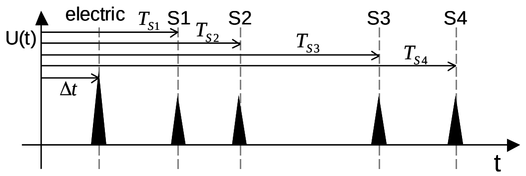

Figure 4: Schematic visualization of acoustic pseudo-times in reference to the (unknown) electric PD signal

Multiplying pseudo-times with a propagation velocity yields pseudo-ranges. This term is used more frequently in the satellite-aided geodesy. All-acoustic measurements with four or more sensors act like an "inverse" satellite-receiver positioning problem. In the GPS the satellites must have a precisely synchronized system time (receiver not synchronized) which means for PD localization one is forced to start recording acoustic signals simultaneously. The PD-localization counterpart for the "receiver" time offset between GPS-receiver and sending satellite is not having a coincidence between PD-event and measurement time-origin. 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.

The non-linear observation equations of the pseudo-time approach in the four sensors case (no system over-determination) with the four unknowns x, y, z and Δt are as follows:

$$(x-x_{s1})^2+(y-y_{s1})^2+(z-z_{s1})^2=(v_s\cdot(T_{S1}-\Delta t))^2 \quad \text{(3a)},$$

$$(x-x_{s2})^2+(y-y_{s2})^2+(z-z_{s2})^2=(v_s\cdot(T_{S2}-\Delta t))^2 \quad \text{(3b)},$$

$$(x-x_{s3})^2+(y-y_{s3})^2+(z-z_{s3})^2=(v_s\cdot(T_{S3}-\Delta t))^2 \quad \text{(3c)},$$

$$(x-x_{s4})^2+(y-y_{s4})^2+(z-z_{s4})^2=(v_s\cdot(T_{S4}-\Delta t))^2 \quad \text{(3d)}.$$

The observation equations (3a-d) become symmetric due to the fact that the unknown time offset Δt is contained in all pseudo-times T_{Si}. With the relation

$$T_{S1}-\Delta t=T \quad (4)$$

one can calculate in a second step the time the PD-event took place. Furthermore the two variants for the system of non-linear observation equations are interconnected through equation (4).

3.3 SOLUTION STRATEGIES

Non-linear equation systems 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. In PD localization problems reasonable initial values are not ad hoc available all the time though a number of plausibility checks can be accomplished. One possibility is defining the origin of the coordinates system in one corner in a way that the transformer housing encloses only positive positions. So negative localization results must be bogus. Other possible plausibility checks are of course related to the physical character of the PD itself or the inner construction of the transformer. A PD generation process needs for example a sufficiently high potential difference.

The solution of the presented equation systems in both variants could be computed iteratively. Nevertheless a great advantage of the pseudo-time notation is a utilization of direct solution strategies available for GPS-problems [1], [2], [7], [8]. With the use of direct algorithms one gets rid of the initial value dependency or can calculate a starting value for iterative solvers.

Another application of direct solvers for PD localization arises from mixed-acoustic measurements using a non-acoustic signal e.g. an electric or an UHF-signal as triggering for the acoustic channels. Mathematically both combined methods could be treated as absolute time measurements. From an algorithmic point of view this could be handled as pseudo-time measurements with the special case "time offset $\Delta t=0$". To emphasis this fact the second sample of localizations is computed directly using absolute times.

4 LOCALIZATION SOFTWARE

Both methods described – time-differences approach and pseudo-times approach – have been implemented in a localization software called PADIALO (Partial Discharge Acoustic Locating). Figure 5 shows a screenshot of the menu where the user can selects the variant of the non-linear equation system and the solving algorithm.

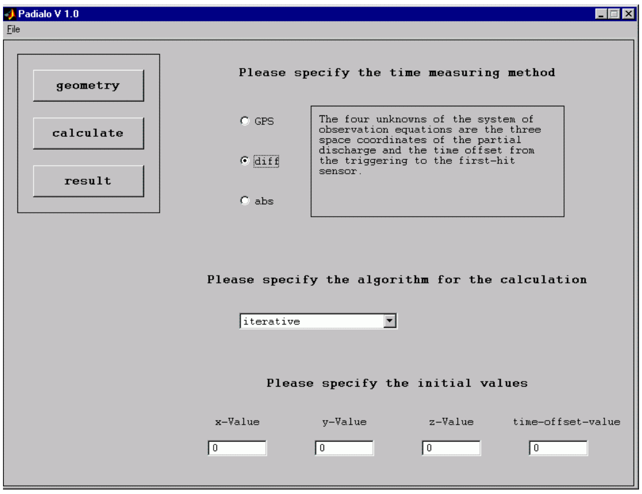

Figure 5: Localization software PADIALO: methods and solving algorithm menu

The third method abbreviation “abs” stand for absolute time measurements. This can be used for already mentioned mixed-acoustic measurements as the UHF-acoustic combination This promising combination in terms of a acoustic sensitivity enhancement is not part of this work but subject of ongoing research.

5 LOCALIZATION SAMPLES

5.1 SMALL TEST TANK WITH ROD-PLANE PD SOURCE

At the Cartesian space coordinates (0,25/0,4/0,26) a rod-plane PD source in a small test tank generated an electric PD level of about 600 pC (which is not the reachable acoustic sensitivity in this example). The emitted acoustic waves have been recorded with six sensors simultaneously. The whole measuring arrangement is shown in Figure 6.

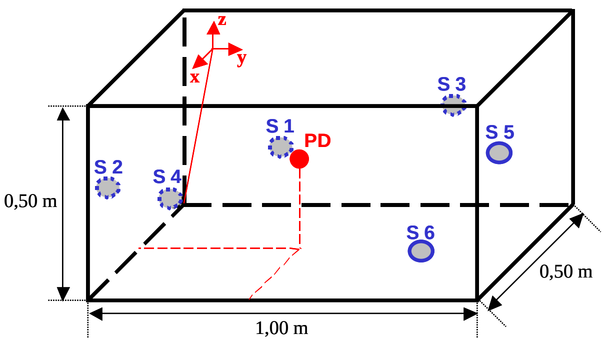

Figure 6: Schematic of small test tank with a rod-plane PD source inserted inside and six acoustic sensors S1-S6

The oil temperature measured was 21.5°C resulting in a sound velocity v_s of about 1410 m/s [5]. The positions of the inserted PD source and the attached acoustic sensors are brought together in Table 1. The actual measured pseudo-times and the later on calculated time-differences can be compared in Table 2.

Object	x [m]	y [m]	z [m]
PD	0.25	0.40	0.26
S1	0	0.245	0.16
S2	0.445	0	0.275
S3	0	0.675	0.27
S4	0.035	0	0.03
S5	0.425	1	0.36
S6	0.5	0.835	0.135

Table 1: Positions of the inserted PD source and the acoustic sensors respectively

Sensor	T_{Si} [ms]	Difference	τ_{1i} [ms]
S1	3.43875	S2–S1	0.1175
S2	3.55625	S3–S1	0.05325
S3	3.49200	S4–S1	0.14625
S4	3.58500	S5–S1	0.16625
S5	3.60500	S6–S1	0.14825
S6	3.58700	-	-

Table 2: Measured pseudo-times T_{Si} and calculated time-differences τ_{1i} of the six sensors

The computations of the PD origin were carried out for both approaches iteratively. The results are given in Table 3 for an initial value [0 0 0 0]. To point out the mentioned initial value dependency: using all six sensors and initial value [0.5 1 0.5 1] yields absurd positions after relatively few iteration steps (29 and 55) for both approaches.

Used sensors	x [m]	y [m]	z [m]	No. Iterations
Time-differences approach				
1, 2, 3, 4, 6	0.246	0.409	0.218	47
1, 2, 3, 4,5, 6	0.242	0.427	0.330	139
Pseudo-time approach				
1, 2, 3, 4, 6	0.246	0.409	0.218	18
1, 2, 3, 4, 5, 6	0.242	0.427	0.330	37

Table 3: Localization results for the different approaches using an iterative solver (initial value [0 0 0 0])

The iteratively gained offset-time Δt information for the pseudo-time approach in Table 3 is omitted because of the good agreement to the direct calculations in Table 4.

Used sensors	x [m]	y [m]	z [m]	Offset Δt [ms]
1, 2, 3, 4	0.205	0.380	0.305	3.2
1, 2, 3, 6	0.243	0.406	0.197	3.2
4, 2, 3, 6	0.248	0.409	0.218	3.2
Mean-values	0.232	0.398	0.24	3.2

Table 4: Localization results for the pseudo-time approach using the direct multi-polynomial solver [1]

The utilized direct algorithm based on multi-polynomial resultants [1] can only use four sensors per calculation. Quad-tupels containing sensor 5 yield absurd results. Checking the time signal of sensor 5 revealed that it was problematic reading the time information. Hence this direct solver could serve as sensitive indicator for poor time measurements and help to give certain weightings for the different time information gathered from the sensors

5.2 HIGH VOLTAGE WINDING IN REAL TRANSFORMER HOUSING

A oil-immersed high voltage winding in a transformer housing with dimensions 1.77m in x-direction (length), 0.77m in y- direction (width) and 1.56m in z- direction (height) situated in the high voltage laboratory of the institute is pictured in Figure 7.

Figure 7: Transformer tank with high voltage winding

PD at the inner side of the winding was stimulated with an electrode on ground. The electric PD level was about 491 pC. High signal/noise-ratios were featured by the time signal, so much smaller levels could have been resolved. The oil temperature in the tank was again 21.5°C and the sound velocity v_s used for the calculations 1410 m/s. The positions of the various objects in this arrangement are collected in Table 5. The measured pseudo-times (here with the special case "time offset $\Delta t=0$") and the calculated time-differences are content of Table 6.

Objects	x [m]	y [m]	z [m]
PD	0.71	0.225	0.875
S_1	0	0.39	1.18
S_2	0.82	0	0.85
S_3	1.15	0	1.19
S_4	1.77	0.39	0.78
S_5	1.11	0.78	0.79
S_6	0.805	0.78	1.205
S_7	0.435	0.78	0.77

Table 5: Positions of the stimulated PD and the acoustic sensors respectively

Table 7 and Table 8 give the computed results for the PD origin with iterative means and the direct GPS solver respectively. Satisfying agreement with the measured PD position presented in Table 5 is accomplished with both solving methods. Whereas no initial value must be guessed while using the direct solver.

Sensor	T_{Si} [ms]	Difference	τ_{1i} [ms]
S_1	0.547	S1–S2	0.411
S_2	0.136	S3–S2	0.178
S_3	0.314	S4–S2	0.679
S_4	0.815	S5–S2	0.242
S_5	0.378	S6–S2	0.294
S_6	0.43	S7–S2	0.253
S_7	0.389	-	-

Table 6: Measured pseudo-times T_{Si} (special case with $\Delta t=0$) and calculated time-differences τ_{1i} of the seven sensors

The results of the quad-tupels containing sensor 4 (highlighted in Table 8) show obviously the indicator function for inaccurate time-measurements of the used direct algorithm. Inspection and comparisons of the acoustic time signals confirm this fact. At the same time it can not be stated that a "weak" time information must lead to a bad result as sensor 4 works fairly well with over-determined iterative calculations in Table 7.

Used sensors (only No.)	x [m]	y [m]	z [m]	No. Iters.
Time-differences approach				
1, 2, 3, 4, 5, 6, 7	0.705	0.290	0.950	42
1, 2, 3, 4,5, 6	0.718	0.279	0.980	134
1, 2, 3, 4, 5	0.722	0.299	1.001	25
1, 2, 3, 5, 6, 7	0.784	0.211	0.793	28
1, 2, 3, 6, 7	0.775	0.208	0.811	24
1, 3, 6, 7	0.789	0.173	0.747	35
⋮	⋮	⋮	⋮	⋮

Table 7: Localization results for the time-differences approaches using an iterative solver (initial value [0 0 0 0])

Used sensors (only No.)	x [m]	y [m]	z [m]	Δt [ms]
1, 2, 3, 4	0.679	-0.04	1.045	-51.22
1, 2, 4, 6	Complex solution			
1, 4, 5, 7	Complex solution			
1, 2, 3, 5	0.792	0.267	0.912	-83.38
1, 2, 3, 6	0.748	0.174	0.986	-40.65
1, 2, 3, 7	0.795	0.273	0.905	-87.90
2, 3, 5, 7	0.783	0.268	0.917	-87.48
2, 3, 5, 6	0.890	0.237	0.840	-55.24
1, 2, 5, 6	0.730	0.26	0.709	-116.0
⋮	⋮	⋮	⋮	⋮
Mean-values (without S4-combinations)	0.790	0.247	0.878	-78.44

Table 8: Localization results for the pseudo-time approach using the direct multi-polynomial solver [1]

5.3 ONSITE ALL-ACOUSTIC LOCALIZATION WITH FOUR SENSOR SIGNALS

An onsite all-acoustic measurement was performed at a 200 MVA single-phase transformer which gas-in-oil diagnosis indicated PD. During an offline applied voltage test an electric PD measurement revealed PD levels up to 600 pC and a acoustic measurement recorded an impulse on four sensors simultaneously [6]. The oil-temperature was about 26 C (which corresponds to 1387m/s sound velocity) according to information from the operating company. Figure 8 pictures the top view of the housing of the transformer with the sensor positions and the iteratively calculated PD location whereas Figure 9 presents a side view. Table 9 gives the corresponding exact Cartesian positions. The direct solver yields a complex solution due to "weak" time information. Because of that the acoustic measurement will be repeated online soon to confirm the localization result.

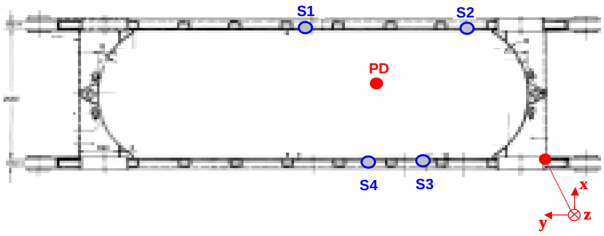

Figure 8: Top view of the housing of a 200 MVA transformer with four acoustic sensors on his outside and the PD location inside

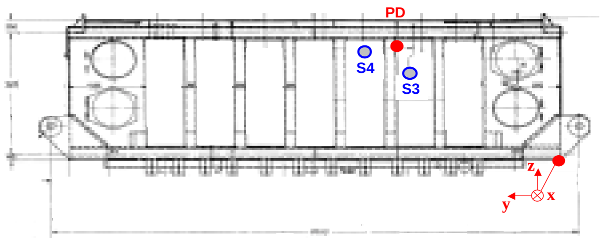

Figure 9: Side view of the housing of a 200 MVA transformer (high voltage section) showing the height of the PD location

Objekt	x [m]	y [m]	z [m]
PD calc.	1.47	3.01	2.23
S1	2.53	4.46	2.07
S2	2.53	1.8	1.38
S3	0	2.57	1.85
S4	0	3.41	2.2

Table 9: Positions of the iteratively calculated PD source and the acoustic sensors respectively

6 CONCLUSION

Depending on the PD failure type or position respectively an all-acoustic PD localization ca be managed. No electric triggering signal, as known in laboratories, is needed. Main problem occurring in online measurements is a lack of enough acoustic impulses simultaneously recorded hence not enough traveling times to render a localization are available. Mixed-acoustic methods like a UHF-acoustic combination could help to overcome this constraint. Direct solvers from the satellite-aided geodesy field offer some valuable features as being independent from initial values. Combinations of iterative and direct solvers could furthermore bring advantages in terms of assessing the quality of a localization result.

REFERENCES

[1] J. L. AWANGE, E. W. GRAFAREND, *Algebraic Solution of GPS Pseudo-Ranging Equations*, Journal of GPS Solution, Vol. 5(4), 2002

[2] S. BANCROFT, *An algebraic solution of the GPS Equations*, IEEE Transactions on Aerospace and Electronic Geodaetica, Vol. AES-21, 1985

[3] E. GROSSMANN, K. FESER, *Improvement of sensitivity in online PD-measurements on transformers using acoustic emission techniques (AET)*, 12th International Symposium on High Voltage, Bangalore, India, 2001

[4] E. GROSSMANN, *Akustische Teilentladungsmessung zur Überwachung und Diagnose von Öl/Papier-isolierten Hochspannungsgeräten*, Dissertation, University of Stuttgart, 2002.

[5] E.HOWELLS, E. T. NORTON, *Parameters affecting the velocity of sound in transformer oil*, IEEE Transactions on Power Apparatur and Systems, Vol. PAS-103, No. 5, May 1984

[6] R. Huber, *Integriertes Überwachungskonzept für Großtransformatoren unter mehrstufigem Einsatz von offline und online Methoden*, Micafil Symposium, Stuttgart, Germany, 2004

[7] L. O. KRAUSE , *A Direct Solution of GPS-Type Navigation Equations*, IEEE Transactions on Aerospace and Electronic Systems 23, 1987

[8] A. KLEUSBERG, *Analytical GPS navigation solution*, Quo vadis geodesia...? Festschrift for E. W. Grafarend on the occasion of his 60th birthday, Eds. F. Krumm and V. S. Schwarze, Report Nr. 1999.6-1, 1999

[9] S. M. Markalous, E. Grossmann, K. Feser, *Online acoustic PD-measurements of oil/paper-insulated transformers- methods and results,* 13th International Symposium on High Voltage, Delft, Netherlands, 2003