Detektion und Ortung von Teilentladungen durch UHF Messmethode
Detection and localization of partial discharges with UHF measuring method

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Kurzfassung

Die Zuverlässigkeit elektrischer Energienetze hängt von der Qualität und der Verfügbarkeit elektrischer Betriebsmittel ab, wie z. B. Transformatoren. Lokale Fehler innerhalb der Isolationen können zu elektrischen Durchschlägen führen, die hohe Ausfallkosten nach sich ziehen können. Um diese zerstörenden Ereignisse zu verhindern, werden Transformatoren vor der Inbetriebnahme und zur Wartung auf Teilentladungsaktivitäten getestet. Mit einer weiteren im Beitrag vorgestellten Untersuchung wird belegt, dass sich die UHF Signale im Inneren des Transformators mit moderater Dämpfung ausbreiten können. Daher ist die UHF Messmethode nicht nur störunempfindlich sondern die Ergebnisse von Vor-Ort-Messungen sind auch hinsichtlich ihrer Empfindlichkeit belastbar. Ein weiterer wichtiger Schritt zur Risikobeurteilung von TE im Transformator ist die Kenntnisse über ihre Position. Im Beitrag werden Untersuchungen vorgestellt, ob UHF-Signale verwendet werden können, um durch Laufzeitdifferenzen die geometrische Lage der TE zu bestimmen. Erste Messungen zur Laufzeitbestimmung von mehreren UHF Sensoren an Transformatoren im Feld werden vorgestellt. Im Beitrag wird weiterhin ein Beispiel einer erfolgreichen Ortung präsentiert, bei der UHF Signale von mehreren UHF Antennen sowie akustische Signale benutzt wurden.

Abstract

The reliability of electrical energy networks depend 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. To prevent these fatal events power transformers are tested on partial discharge (PD) activity before commissioning and currently also during service. The current work deals with the electromagnetic method, also known as UHF-Method. The UHF-Method with a bandwidth from 300 MHz to 3 GHz bases on the fact, that PD inside oil filled transformers emits electromagnetic waves measurable with oil valve probes inside the transformer tank. The characteristics of low attenuation of electromagnetic waves traveling through different insulating materials and structures like pressboard, oil and windings are investigated on power transformers in field. An important step for risk evaluation in case of PD is locating the PD source geometrical within the transformer. The paper presents the possibility of locating PD sources by using run times of UHF signals and acoustic measurements.

1 Introduction

Defects in transformer insulation cause partial discharges (PD), which can progressively degrade the insulating material and possibly lead to electrical breakdown. Therefore, early detection of partial discharges is important [1]. PD measurements can also provide information about the ageing condition of transformers and thus enable conclusions about their lifetime.

The so called UHF PD measuring method (UHF: Ultra High Frequency) bases on the fact that PD under oil are very fast electrical processes and radiate electromagnetic waves with frequencies up to the ultrahigh range (UHF: 300 – 3000 MHz). The electromagnetic waves are sensitively detectable with UHF probes, see Figure 1. The probes can be inserted into the transformer during full operation using the oil filling valve. As a result of shielding characteristics of the transformer tank against external electromagnetic waves, a clear decision can be made concerning the PD activity of the test object.

Figure 1: UHF PD probe for standard oil filling valve

The moderately attenuated propagation of UHF waves inside transformer tanks is proofed on transformers planned for scrapping. This was shown in laboratory research in [2], was firstly proofed in [3] and is investigated continuatively in this paper.

An important step for risk evaluation in case of PD is locating the PD source geometrical within the transformer. The paper presents the possibility of locating PD sources by using runtimes of UHF signals and signals of acoustic measurements.

2 Attenuation inside transformer

PD signals might be measured and quantified with regards to a sensitivity check in apparent charge (pC) within large power transformers with UHF probes. Precondition is that electromagnetic waves emitted by a PD can be measured everywhere in the transformer without or at least with known loss of UHF signal power. For sensitive measuring results, there should be no significant influence of the internal structure on the propagation of UHF signals.

For analysing that characteristic of UHF propagation inside power transformers, a 210 MVA grid coupling transformer intended for scrapping was prepared for some experiments. The transformer was oil free but with intact tank, which acted as a faraday cage for external disturbances. More important, the transformer included it complete active part. To get several different locations for propagating electromagnetic waves through the transformer, 20 boreholes (Ø 5 mm) were drilled into the tank wall at various positions around the transformer tank. The locations of the boreholes no. 15 – 20 are exemplary shown for the backside of the transformer in Figure 2.

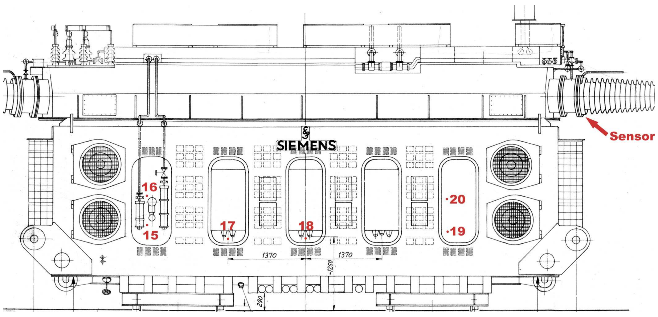

Figure 2: Position of boreholes in transformer tank

Since the transformer is intended for scrapping, this kind of destructive measurement is possible. For emitting artificial UHF impulses a 10 cm long monopole [3] was pushed through the boreholes into the transformer. With a signal generator at maximum amplitude (60 V at 50 Ω) pulses were injected. The emitted UHF waves inside the transformer are measured with a UHF probe at the oil filling valve, see Figure 3.

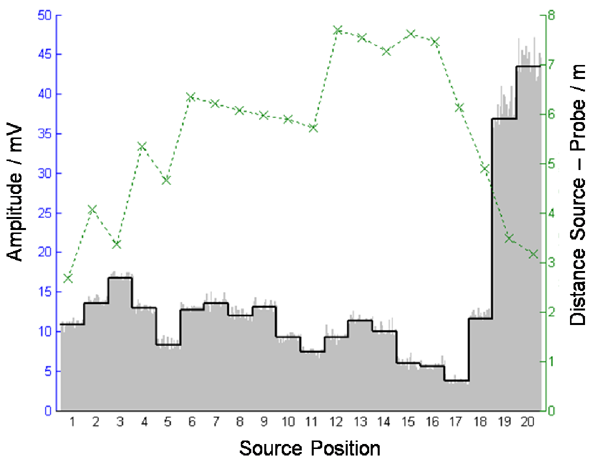

Figure 3: Maximum amplitudes of UHF waves

In order to have maximum sensitivity the UHF probe was pushed maximally into the tank (12 cm into the tank). The measurements were done with an oscilloscope of 3 GHz analogue bandwidth and a 290 MHz high pass filter. The diagram in Figure 3 represents the maximum amplitude of UHF signals measured with the UHF probe, over the position of the source (borehole with monopole). Additionally it shows the shortest distance between source and probe.

It is noticeable that the measurements at the positions 19 and 20 cause higher amplitudes than at the other positions. The reason is that these two positions have the shortest travelling path and no obstacles are in the propagation path, see Figure 4.

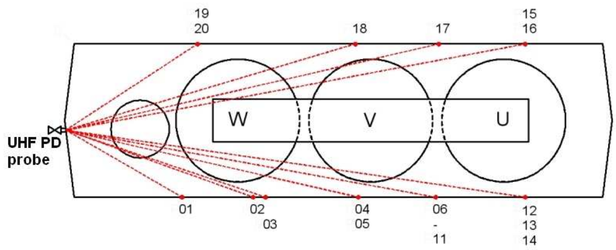

Figure 4: Propagation paths for emitted UHF waves to UHF probe

In Figure 5 the attenuation in terms of dB and the attenuation in terms of dB/m over the position of the UHF source are shown. All measured values are thereby related to the highest measured amplitude (43.4 mVs), here position 20, drilled behind the tap changer drive.

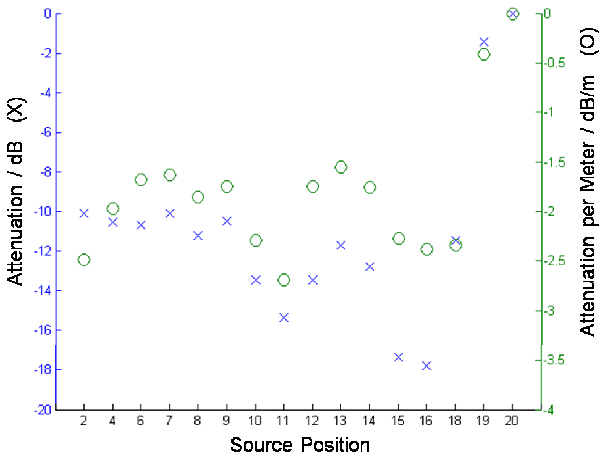

Figure 5: Attenuation of UHF signals inside transformers

In the diagram not all 20 positions are specified. P1, P3, P5 and P17 were not considered, since the monopole was not completely insertable into the tank. Within 14 measured positions an averaged attenuation of 12.6 db and an averaged attenuation per meter of 2.0 dB/m were calculated. A similar measurement was already accomplished in [3]. The attenuation had a bigger deviation with a higher value (up to 6 dB/m). That might be explained by usage of the presented monopole as receiving antenna, which is less sensitive than the UHF probe in the presented measurements here. Rough estimation with help of the propagation paths in Figure 4 is that a signal, in whose propagation path lies a complete winding is attenuated around – 6 db. If the winding is only touched by the signal, then the attenuation is only half (- 3 db). If the step changer lies in the propagation path, an additional attenuation of – 2 db is to be expected.

For absolute attenuation it is noticeable that the values are close together except for a few positions. Position 11 lies between two 110 kV bushings, P15 and P16 has the longest travelling path through the active components, see Figure 3.

Because of the high UHF signal-to-noise ratios and regarding the strong amplitudes, the measured attenuation does not undermine the sensitivity of the UHF method in general. Additionally broadband amplifiers can be used for measuring UHF signals sensitively.

Comparison of attenuation factors of the complete active part arrangements from above (e.g. propagation path through complete HV/LV-windings etc.) with the results for single, generic structures as e.g. part of a disc-winding (attenuation around 2 dB) or a 0.5 cm gap in a metal plate of (attenuation around 3 dB) [2] show similar values.

Active parts of transformers have strong influence on UHF signals and the resulting attenuation is not linear to the distance. More experiments like mentioned above with different transformers will show, if the attenuation is within the same range or even predictable for identical transformer types. Because of the distance dependent attenuation, it might be impossible to determine the level of a PD without knowing its location and therewith the possible spread of attenuation of the UHF waves on the propagation path to the UHF probe.

3 Localization of PD by only UHF signals

Onsite but offline measurements were made on a generator step up transformer with 120 MVA. The transformer possesses two oil filling valves, see Figure 6 and 7.

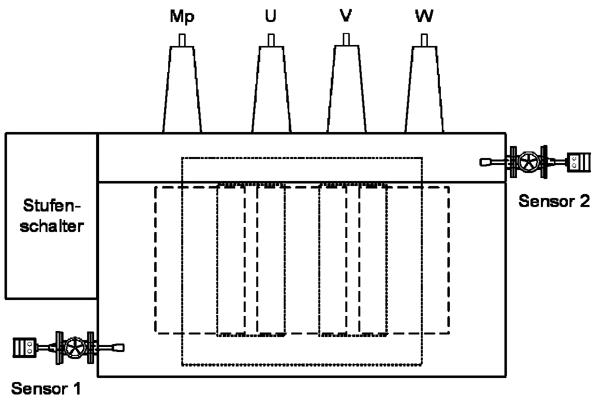

Figure 6: 120 MVA Generator Step-up Transformer

The first valve is underneath the step changer housing on height of the lower core. The second valve is on the opposite side underneath the oil expansion tank in the cover of the transformer.

Figure 7: UHF probes installed at 120 MVA generator step up transformer

The first measurement, a so-called dual port Performance Check [4], demonstrates the sensitivity of the measuring system. Wide-band signals of a signal generator (60 V at 50 Ω) are fed over the first UHF sensor into the transformer housing and measured with the second UHF sensor. Figure 8 represents the received time signal and its FFT. This measurement took place without high voltage.

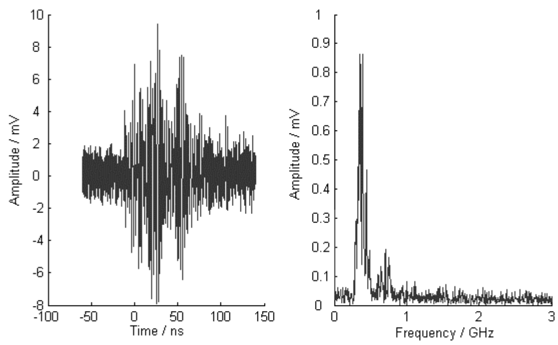

Figure 8: Dual port Performance Check

From the illustration it is evident that a wide-band signal (right, frequency portions up to 1 GHz) was travelling through the transformer and its active part. Likewise the signal-to-noise ratio is sufficient in the time signal (left). Therefore the sensors are correctly installed and attached to the measuring instruments. A sensitive UHF measurement is possible.

It was possible to measure UHF signals with both probes, see figure 16. The red signals was recorded with the probe 1 below the tap changer, the blue signals was recorded with the probe 2 in the transformer cover on the opposite side.

Both Figures show two time signals of different PD sources. In Figure 9 (left), probe 1 measured the UHF signals first and additionally with higher amplitude than probe 2. Hence it could be stated, that the PD source is nearer to probe 1. In Figure 9 (right) the amplitudes of both probes are nearly the same and the signals have just a small run time difference. According to that it could be stated, that the PD source of that signals might be in the middle of the transformer because of the same distances and run times between the probes. During 30 seconds about 100 time signals of the UHF PD probes were recorded. In order to locate the PD, the running times were calculated by finding the starting point of the signals by defining a threshold value. That kind of definition of the beginning of a signal is quite inaccurate, but it is sufficient however for a first impression.

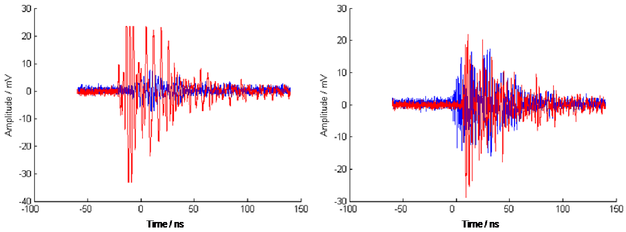

Figure 9: Signals measured with UHF PD probes at different locations

By dividing the run times through the speed of UHF waves in oil [5], the distance between PD source and probe is calculated. A positive value means that the PD defect is nearer to probe 1, a negative nearer to probe 2. With that information it might be possible to identify the phase, where the PD occur. A statistic evaluation of the run time differences of around 100 signals is shown in Figure 10.

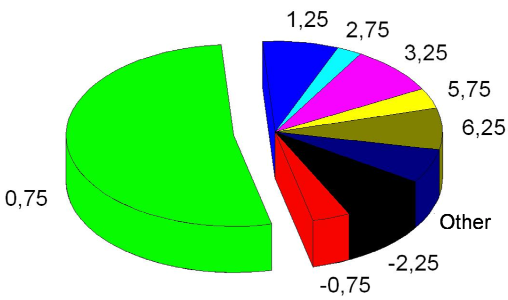

Figure 10: Spatial deviation from middle position of PD in meter

According to the IEC 60270 measurements at the same time [6], four different PD sources might be active inside the transformer. One cluster (see Figure 17, "0,75") is recognizable, the most active PD source seems to be in the middle of the transformer. According to the results in [6] the PD source in phase L2 seems to be located with a difference of 75 cm from middle position.

The evaluation interval of these data amounts to ± 25 cm and/or ± 2.5 ns. Under „Other" PD events are summarized, which arose only once. There are no other clear recognizable clusters correlating to only one PD source. Due to that it might be that there are more than three other PD sources active. Or the runtime determination of the UHF waves is quite inaccurate because UHF waves might propagate chaotically through the tank: In that case, one and the same source produce more than one resulting run time difference.

Concluding it could be stated, run time differences are measurable in UHF frequency range. For exact localization algorithm at least four UHF probes are needed. But normally transformer haven't more than three oil filling valves. Therefore the acoustic measurements will still be needed in future. In the presented case, acoustic measurements didn't succeed, because of the overlapping signals of more than one PD source.

4 PD localization with combined UHF and acoustic measurements

Because of gas in oil values which indicates internal PD a 333 MVA Transformer was tested on line on PD. Because of higher noise level in field, UHF PD Measurements for PD detection were performed in combination with acoustic measurements for PD localization.

4.1 UHF PD measurements

The transformer consists of three oil filling valves and three comparable UHF Sensors were installed. Fig 11 shows the positions of the UHF probes (UHF 1 – UHF 2). Two are opposite against each other at the top of both front ends and the third is located at the bottom in the middle of the transformer side.

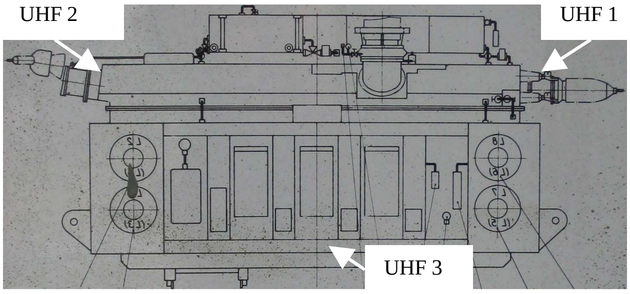

Figure 11: Positions of UHF Probes at 333 MVA transformer

First, the so called dual port Performance Check was done, compare to chapter 3. Artificial UHF impulses was injected at each probe with a signal generator (60 V at 50 Ω). It was not possible to detect the artificial impulses at any combination of emitting and receiving probe. The transformer manufacturer declared the reason that inside the oil filling valves tubes directing the oil flow around the winding are installed. According to the unsuccessful dual port performance check it could be stated, that the probes are electro magnetically decoupled from each other. Furthermore they might be also shielded against UHF pulses from internal PD.

But nevertheless, at nominal voltage UHF signals from internal sources were detectable with all three probes. I.e. the internal PD cause UHF signals with higher energy than the artificial impulses. The dual port Performance Check is than just a worst-case estimation of the sensitivity. But in case it's not successful sufficient sensitive UHF measurements are still possible.

In Figure 12 the measurable signals of the UHF probes are shown.

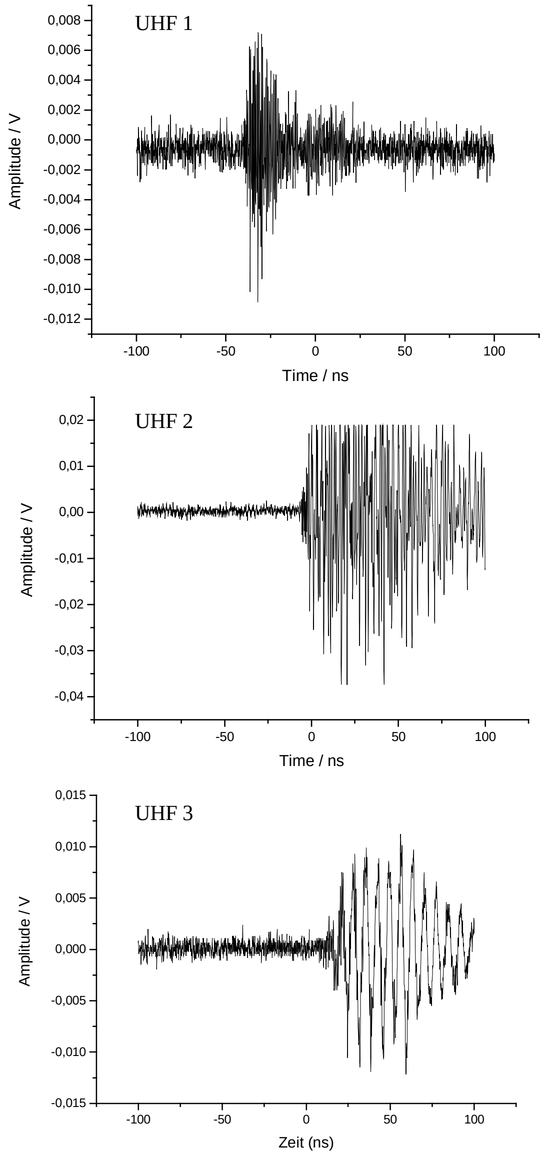

Figure 12: Measurable run time differences between three UHF probes at different locations

Recognizable are run time differences in the range of nano seconds (ns). Taking run time differences caused by different lengths of measuring lines into account, a first estimation of the geometric PD location led to the tap changer. That is supported by the measured UHF amplitudes of the three UHF probes. The probe nearest to the tap changer (probe UHF 2) has the highest reading output with over 40 mV, whereas the other probes didn't reach more than 10 mV. According to that, probe UHF 2 was used for triggering and determining the starting time for measuring run time differences.

Simultaneous IEC 60270 measurements show highly affected measurements because of audible corona discharges. By using frequency analyses and phase related UHF PD pattern the UHF Measurements are proofed to be not affected by the external corona discharge.

An exemplary frequency analysis of the measured signal of probe UHF 2 proofed the shielding characteristic of the tank, see Figure 13.

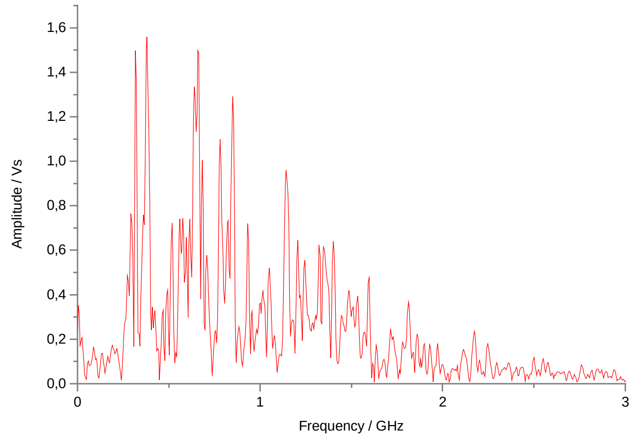

Figure 13: Frequency analyse of probe UHF 2

This signal features frequency portions up to 2 GHz which is normally emitted by a broad band emitter of UHF waves like an internal PD in oil. External noise would have been narrow banded, e.g. at around 500 MHz for digital video broadcasting or around 900 MHz for global communication systems. For further proof that the signals correlate to a PD, PRPD´s of the signals were recorded, synchronized to the voltage supply of the measuring unit (LDS6/UHF) [7]. Similar to the IEC 60270 PD measurements typical pattern are visible, see Figure 14.

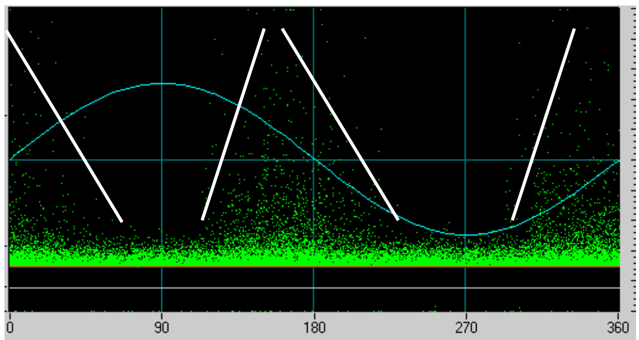

Figure 14: UHF PRPD of signals of probe UHF 2

Phase stabile UHF pulses correlates to PD and with the presented proof for the shielding it could be stated that they measured signals correlate to internal PD.

4.2 Acoustic PD measurements

PD effects develop acoustic waves, which are measured with piezo-electric microphones. They measure the acoustic signals in a frequency range between 50 and 200 kHz. Due to the ambient noise (corona in air) and the inherent noises of the transformer the noise level in field for on line measurements is high and sensitive acoustic measurement are almost not possible [8]. Additionally acoustic signals of PD experienced high attenuation inside transformers because of the internal structures.

Summarizing, exclusive acoustic PD measurement or on-line monitoring is only limited useful. To increase the sensitivity of acoustic measurements the method is coupled with the more sensitive UHF measuring method. UHF signals are used as trigger signal to activate the acoustic measurement during the occurrence of UHF PD signals. By calculation averaged signals in time domain (Averaging) the acoustic PD pulses overlay constructional whereas the white background noise is averaged to zero. Figure 15 defines the positions of the used acoustic sensors (A1 – A6).

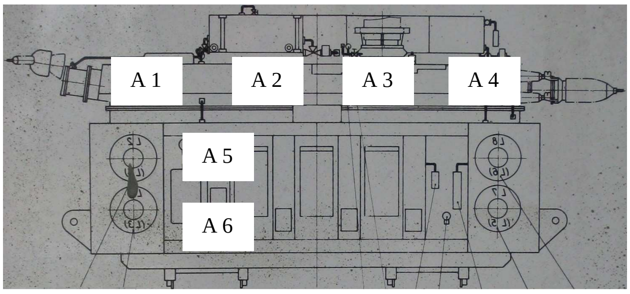

Figure 15: Position of acoustic sensors

4.3 PD localization

UHF measuring method is based on electromagnetic waves, which spread with almost speed of light in the transformer. The speed of acoustic waves amounts to 1400 m/s, i.e. running times within the range of milliseconds are expected, supposed that UHF signals are detected starting time of PD. From the running times of the individual acoustic sensors a calculated geometrical distance to the source of PD results in a sphere inside the transformer. With at least three acoustic sensors with associated running times it is possible to determine the intersection of the spheres to determine thus the PD location. The running times of the acoustic signals can be computed objectively with the help of the Hinkley criterion [2]. It is based on the signal energy of the measured signal and results in an absolute minimum for the starting point of the signal.

Drawn in Figure 16 the supposed position of the PD source is in the range of the tap changer.

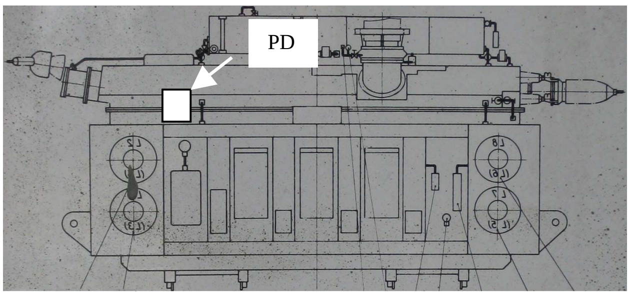

Figure 16: Position of localised PD

Geometrical inaccuracy is thereby within the range of approx. 40 cm on all space axes. This inaccuracy is caused by using different combinations of sensors and run time differences and different localization methods [2].

5 Conclusion

The moderately attenuated propagation of UHF waves inside transformer tanks was proofed on a transformer planned for scrapping. The averaged attenuation factor is 2 dB/m. Because of high UHF signal-to-noise ratios and regarding the strong amplitudes, the measured attenuation does not undermine the sensitivity of the UHF method in general. Additionally broadband amplifiers can be used for measuring UHF signals sensitively. UHF oil filling valves are often electro magnetically shielded from the internal tank by tubes for directing the oil flow. But sensitive UHF measurements are still possible.

Run times measured in the UHF range can be used for geometrical PD location. The accuracy seems to be enough to determine the phase where the PD is located. Additionally different measurable UHF amplitudes allow an estimation of the PD location. With that estimation acoustic sensors can be placed near to the PD source at the transformer tank. Due to the fact, that normally no transformer offers more than three UHF oil valves, for geometric locating the acoustic measurement method is used. In case of more than one PD source acoustic localization becomes impossible because of overlaid signals.

6 Literatur

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