SENSITIVITY LIMITS OF UHF PD MEASUREMENTS ON POWER TRANSFORMERS

S. Coenen[1*], S. Tenbohlen[1], S. Markalous[2] and T. Strehl[2]
[1]Institute of Power Transmission and High Voltage Technology, Universität Stuttgart, Pfaffenwaldring 47, 70569 Stuttgart, Germany
[2]LDIC GmbH, Zschoner Ring 9, 01723 Kesselsdorf, Germany
*Email: Sebastian.Coenen@ieh.uni-stuttgart.de

Abstract: The reliability of electrical energy networks depends on quality and availability of the electrical equipment like power transformers. Local failures inside their insulation may lead to catastrophic breakdowns and may cause high outage and penalty costs. To prevent these destroying events power transformers are e.g. tested on partial discharge (PD) activity before commissioning and 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 travelling through different insulating materials and structures like pressboard, oil and windings are investigated on power transformers in field. A still unanswered question to the sensitivity is, if UHF PD signals can be measured in case the PD source is buried deep in the winding, e.g. directly located at the iron core. The paper presents an investigation of that "winding-depend" attenuation of UHF signals. An important step for risk evaluation in case of PD is locating the PD source geometrical within the transformer. The paper presents finally the possibility of locating PD sources by using runtimes of UHF signals.

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 [2]. 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.

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 continuative in this paper.

A still unanswered question to the sensitivity is, if UHF PD signals can be measured in case the PD source is buried deep in the winding, e.g. directly located at the iron core. The paper presents an investigation of that "winding-depend" attenuation of UHF signals.

2. ATTENUATION INSIDE TRANSFORMERS

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 1.

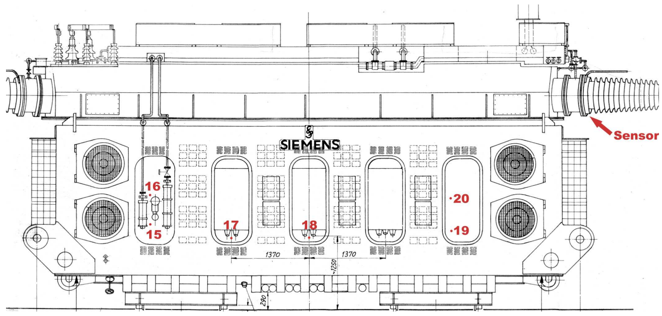


Figure 1: Position of boreholes in transformer tank

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 sensor at the oil filling valve.

In order to have maximum sensitivity the antenna 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 2 represents the maximum amplitude of UHF signals measured with the UHF probe, over the position of the source (borehole with monopole), and additionally the shortest distance between source and probe

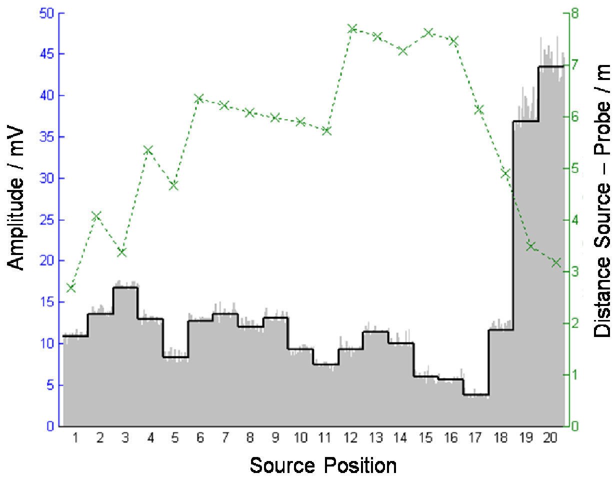


Figure 2: Maximum amplitudes of UHF waves

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 3.

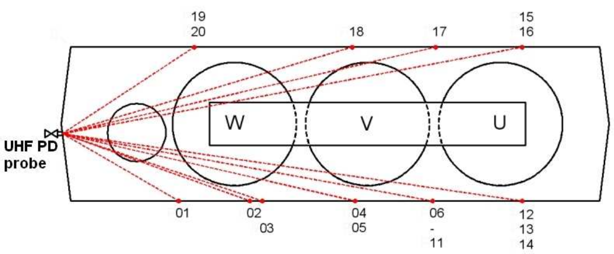


Figure 3: Propagation paths for emitted UHF waves to UHF probe

In Figure 4 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.

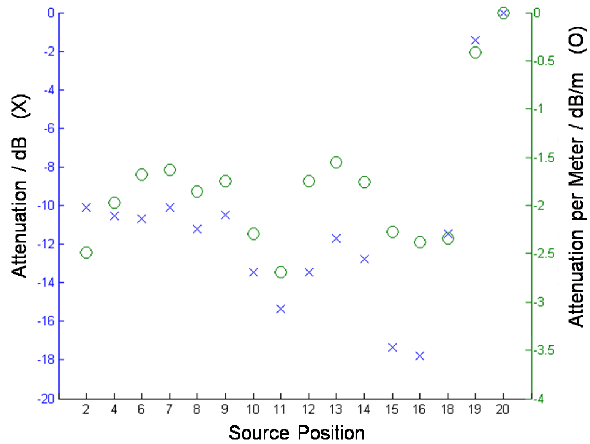


Figure 4: Attenuation of UHF signals inside transformers

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. ATTENUATION INSIDE WINDINGS

A still unanswered question to the sensitivity is, if UHF PD signals can be measured in case the PD source is buried deep in the winding, e.g. directly located at the iron core. In that case the emitted UHF waves must possibly propagate through several disk and/or layers of windings.

3.1. PD source inside winding

First idea to investigate the "winding-depend" attenuation of UHF waves is to shift very small PD sources into existing gaps inside old active parts of transformers. A small PD source can be achieved with an very compact rod-plane arrangement attached on a RG214 cable [3].

Next step is preparing an active part or at least a winding for shifting the PD source inside. In laboratory an active part of a transformer was prepared. By drilling some boreholes into the windings, six different positions occur, where the small PD source can be shifted in. The six drillings (16 mm in diameter) are reaching into the main insulation gap. See position of drillings in Figure 5. Three drillings are in the winding of the left phase, see Figure 5 left (three boreholes, one above the other and distance between the drillings 25 cm). In the middle phase are three boreholes spread around the winding, see Figure 5 middle.

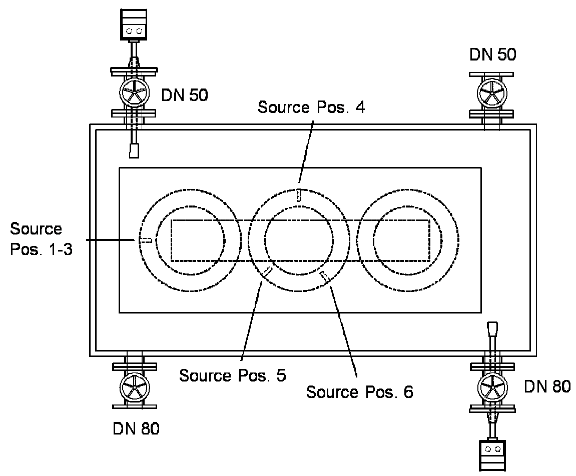


Figure 5: Position of boreholes inside windings

The active part was put into an oil filled tank, which possesses four oil filling valves. For measurement of the emitted UHF waves two UHF PD probes are used. First probe is in the lower DN80 oil filling valve, the second in the upper DN50 oil filling valve at the other side. Both probes are connected by two equal long measuring lines with an oscilloscope of 3 GHz analogue bandwidth.

The IEC measuring method was done simultaneous with the UHF measuring method and the apparent charge and the UHF amplitude of one and the same PD pulse was recorded [3]. While recording e.g. more than 30 signals the natural deviation of PD defects helps to find a correlation between UHF signal amplitude and apparent charge for the used PD sources.

Next step is to compare the UHF readings of the PD sources while the are first INSIDE a winding and second OUTSIDE the winding, see Figure 6.

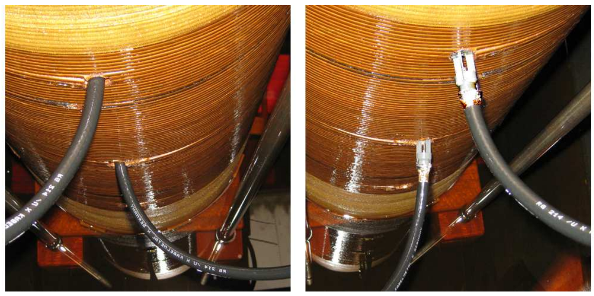


Figure 6: PD source INSIDE winding (left) and OUTSIDE winding

In the first run the PD sources were shifted into the drillings 1 to 6 and the UHF reading over the IEC reading was recorded, see exemplarily for position 1 in Figure 7. In the second run the PD sources are fixed before the boreholes, see Figure 6 (right). Again the simultaneous measurements takes place. In the represented diagrams the green colour marks the measured values of the lower DN80 probe and the red colour those of the upper DN50. With the symbols means „+" the PD source is inside the winding and an „o" it is outside the winding. The straight lines were computed with regression analysis of the smallest error. Figures 7 and 8 represent the measured results of the PD source at position 1.

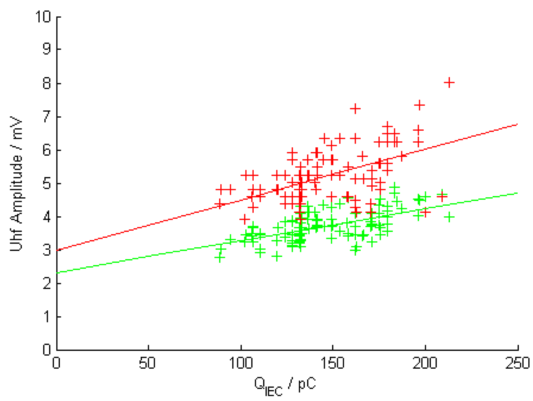


Figure 7: Position 1, INSIDE winding

The measured values of the IEC measurement exhibit approximately the same range of values. The upper DN50 probe (red/dark) measures higher amplitudes than the DN80 probe in the lower oil filling valve (green/bright). Explanation is that the DN50 probe is nearer at the PD source than the DN80 probe, compare Figure 5.

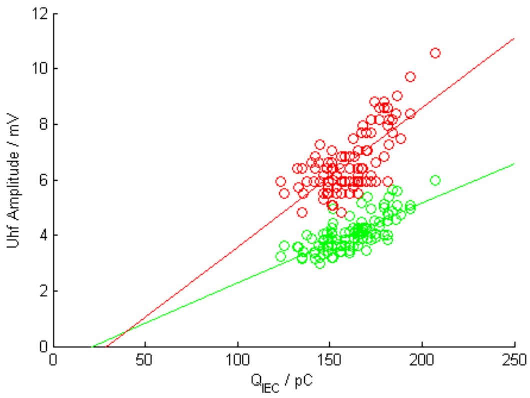


Figure 8: Position 1, OUTSIDE winding

If the PD source is OUTSIDE the winding, higher amplitudes are measurable with the UHF probes than the PD source INSIDE the winding.

This may lead to the expectations that an UHF signal, which must propagate through a winding, will be attenuated. But at position 2 this seems not to be correct any more. In Figures 9 and 10 the results of measurement at position 2 are presented.

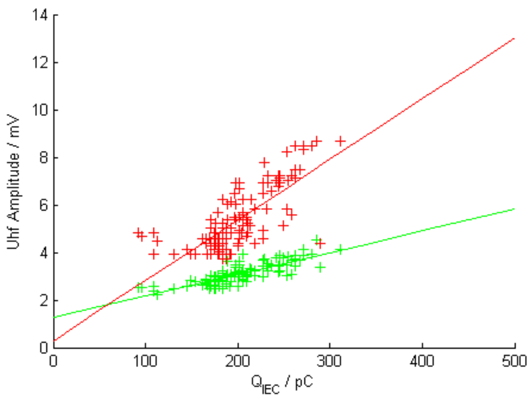


Figure 9: Position 2, INSIDE winding

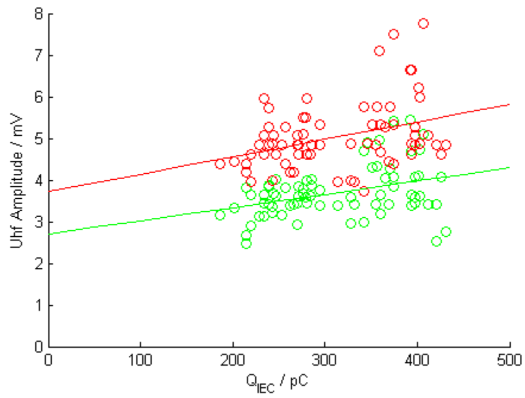
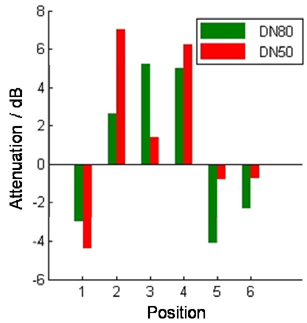


Figure 10: Position 2, OUTSIDE winding

Again the probe at the upper DN50 oil filling valve measures higher levels than the lower DN80 probe. However during measurement with the PD source INSIDE the winding the slope of the regression lines is higher than with the PD source OUTSIDE the winding. I.e. the UHF signal OUTSIDE the winding is more attenuated than INSIDE the winding. A summary of the measured values at all six positions is represented in Figure 11.



Position	Sensor DN80	Sensor DN50
1	- 2,9 dB	- 4,3 dB
2	2,6 dB	6,9 dB
3	5,2 dB	1,3 dB
4	4,9 dB	6,2 dB
5	- 4,0 dB	- 0,7 dB
6	- 2,2 dB	- 0,6 dB

Figure 11: Attenuation of UHF signals inside winding

The signal attenuation is thereby computed with the quotients of the UHF amplitudes at maximum apparent charge level (here: 250 pC). A negative value in the table means, the signal with the PD source OUTSIDE the winding was stronger. A positive value means that the signal with the PD source INSIDE the winding was stronger. The result of the measurement is unexpected: There are just as many positive values as negative values of attenuation. This leads to the assumption that it is all the same, whether the PD source is INSIDE or OUTSIDE the winding.

A reason could be that the radiation behaviour of the PD sources has strong influence. It is possible that the UHF wave of the PD event is not emitted in front at the PD source itself [4]. It might be that the high voltage structure, here the feeding cable, is the origin of the emitted UHF waves.

3.2. Signal generator inside winding

Second idea was to investigate the “winding-depend” attenuation of original UHF waves. In that case artificial UHF pulses of a signal generator were used. The entire measurement set-up is thereby in a completely shielded laboratory with high frequency absorber. Thus the measurements neither contain external disturbances nor reflected internal signals.

As source for the high frequency UHF impulses the monopole of Figure 3 is used with a signal generator. A part of a disk winding of a distribution transformer is used. For comparison the UHF measuring reading was measured with the winding around the UHF source and once without the winding around the source. The winding thereby stands on a copper plate and is covered with another. This is to force the UHF waves through the winding. The experimental set-up is shown in Figure 12.

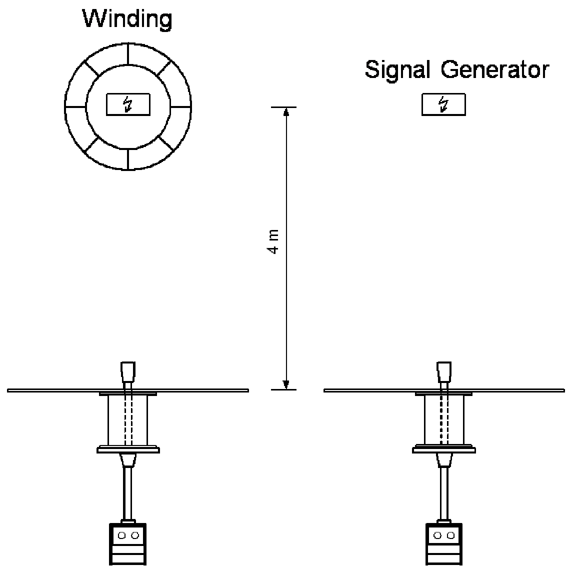


Figure 12: Signal generator inside winding

On the right side the signal generator without winding is presented. Left the arrangement with the winding is to be seen. The distance between UHF source and UHF probe amounts four meters. As measuring antenna a UHF PD probe is used. To arrange the measurement as realistic as possible, the probe is in a tube of 50 mm diameter, which copies the oil filling valve at transformers. At this tube a grounded plate is attached, it represents the grounded transformer housing, see Figure 13.

Figure 13: Winding (left) and UHF PD probe with grounded plate (right)

The unamplified signals were measured in time domain with a 3 GHz oscilloscope and a 290 MHz high pass filter. In Figure 14 the results are presented.

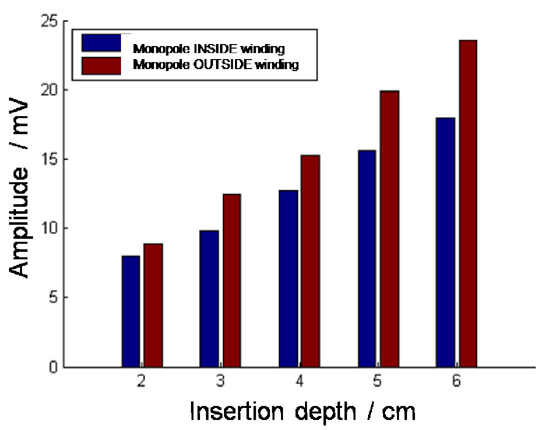


Figure 14: Measured amplitude of UHF PD probe over insertion depth

The arithmetic average value of the measured attenuation is here approximately – 2 dB (- 1.81 dB). With another layer winding an attenuation of - 3.8 dB was obtained with another monopole. This range of attenuation factors confirms the results of measurements from chapter 2.

The windings are of very small design (diameter: 60 cm). In power transformers the used windings are larger. I.e. possible gaps inside the winding are bigger, where the UHF waves can easily propagate through. The attenuation factors might decrease for bigger windings. This should be investigated in future to ensure high sensitive UHF PD measurements.

4. LOCALISATION OF PD BY UHF SIGNALS

Onsite but offline measurements were made on a generator step up transformer 110/10 kV with 120 MVA. The 10 kV windings were used for excitation of the transformer. The transformer possesses two oil filling valves, see Figure 15. 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 15: UHF probes installed at a 120 MVA generator step up transformer

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 16 (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 16 (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.

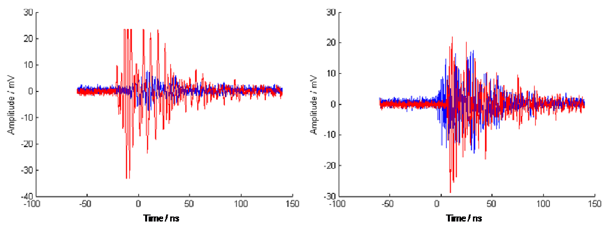


Figure 16: Signals measured with UHF PD probes at different locations

By dividing the run times through the speed of UHF waves in oil [4], 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 17.

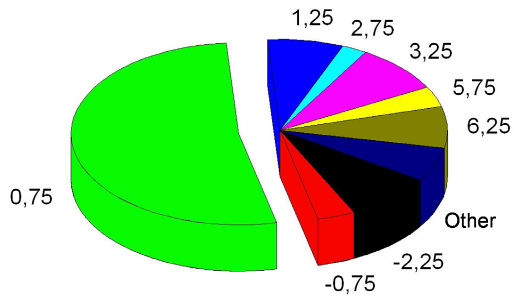


Figure 17: Spatial deviation from middle position of PD in meter

According to the IEC measurements in [5], 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 [5] 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. Maybe there are more than three other sources active, or the runtime detection is so bad or the UHF waves propagate chaotically through the tank that one and the same source produce more than one resulting run time difference.

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 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.

In that case UHF waves propagate around the active parts and might not propagate through the windings. But a still unanswered question regarding sensitivity is, if UHF PD signals can be measured in case the PD source is buried deep in the winding, e.g. directly located at the iron core. In that case the emitted UHF waves must possibly propagate through several disk and/or layers of windings.

For investigation the attenuation caused by windings, two different measurements was performed. First small PD sources were installed at boreholes inside a winding. The results miss a clear statement. That might be explained with the radiation behaviour of the used PD sources and have to be investigated further. Secondly the attenuation factor was investigated on windings in laboratory with use of a signal generator. In that case the attenuation factor of one winding was determined to be in the range of 2 dB, which additionally proof the results of the measurements inside the transformer.

Generally it could be stated that PD might be measurable with UHF PD probes in nearly all cases, because the high voltage structure will radiate the UHF waves independent of the exact position of the PD. That radiation behaviour might be an advantage for sensitivity of the UHF method. But it might be a disadvantage for localisation of PD source by solely measuring UHF waves. In case if the geometry emits the UHF waves, the locating would result in the emitting structure and not the source itself.

Finally a first attempt of using run time differences of UHF waves was performed. Run times can be used for geometrical PD location. The accuracy seems to be enough to locate the PD source at one phase. Due to reflection and the unknown propagation speed, the accuracy decreases.

6. REFERENCES

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