FUNDAMENTAL CHARACTERISTICS OF UHF PD PROBES AND THE RADIATION BEHAVIOR OF PD SOURCES IN POWER TRANSFORMERS

S. Coenen[1*], S. Tenbohlen[1] T. Strehl[2] and S. Markalous[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. 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 based on the fact, that PD inside oil filled transformers emit electromagnetic waves measurable with oil valve sensors inside the transformer tank. For comparable UHF PD measurements for the increasing number of research institutes all over the world, electrical characteristics of the used probes have to be comparable or at least well-known. A possibility of UHF probe standardization basing on the antenna factor is presented. Additionally a general aspect of the UHF method can be concluded regarding the insertion depth of UHF probes inside the transformer tank. Furthermore there is still a discussion about the exact origin of UHF waves or the radiation behaviour of the high voltage structure. The PD source itself, e.g. a point needle arrangement, might be too small for emitting UHF waves like an antenna. An idea of measuring the influence of the structure on the radiation of PD is presented.

1. INTRODUCTION

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

The unconventional 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). Due to the moderately attenuated propagation of UHF waves inside the transformer tank [2], the electromagnetic waves are sensitively detectable with UHF probes, e. g. seen in Figure 1.

Figure 1: UHF PD Probe for standard oil filling valve

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, normally a clear decision can be made concerning the PD activity of the test object.

Due to research and the development progress for UHF PD measuring method, more and more PD probes are used worldwide [3]. The probes differ from each other by design and electrical characteristics so a comparability of UHF PD measurements is not fulfilled. The determination of the antenna factor allows the characterisation for the sensitivity of UHF PD probes. Regarding that sensitivity for future UHF PD measurements can lead to an improvement of the comparability of measurements.

There is still a discussion about the exact origin of UHF waves. The PD source itself, e.g. a point needle arrangement, might be too small for emitting UHF waves like an antenna. The current work presents an idea of measuring the radiation behaviour of PD.

2. CHARACTERISTICS OF ANTENNAS

An antenna has to transfer the received energy of an electromagnetic wave into the energy of a line based signal. Or the other way round to emit electromagnetic waves of an high-frequency generator. Antennas are described by different characteristics, e.g. by the so called antenna factor (A.F.). The A.F. describes the sensitivity of an antenna. It is frequency dependent and forms the relationship between the electrical field strength E received by an antenna and the resulting antenna output voltage U.

$$A.F.(f) = \frac{E\ (f)}{U\ (f)} \tag{1}$$

The term of the A.F. is 1/m and it is usually scaled logarithmically in terms of decibels per meter (dB/m).

For an antenna with low A.F., smaller electrical field strength is necessary to receive a certain electrical signal. The smaller the A.F., the more sensitive the antenna. Figure 2 shows exemplarily the A.F. of an UHF PD probe. As could be seen, a realistic A.F. is not linear over the frequency.

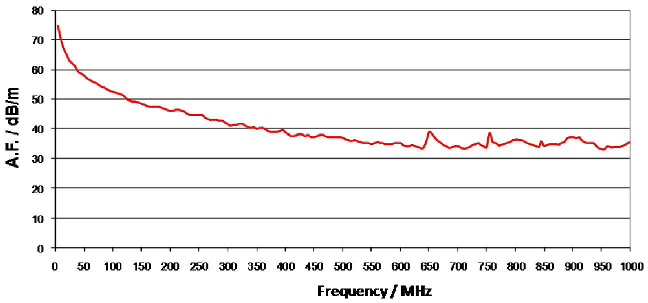


Figure 2: Example of Antenna factor

An ideal A.F. would show a linear correlation between electrical field strength and antenna output voltage for broadband frequency ranges. In that case, measuring results are easy to compare, because all frequency portions are transformed into an output voltage in a linear way. In case if the A.F. is at least well known, the measuring result of the related antenna can be corrected by the frequency dependent transformation of the antenna. With the knowledge of the A.F. of different UHF probes their measuring results became more comparable.

2.1. TEM Cell

An antenna is very sensitive depending its design and size in relation to the received electromagnetic waves. For determining that sensitivity a special environment is necessary without disturbing external electromagnetic waves and reflections of internal electromagnetic waves. Such a measuring environment can be achieved according to different methods: With a particularly furnished antenna measuring room or with the use of a transverse-electromagnetic cell (TEM cell). A TEM cell is an expanded coaxial conductor with two coaxial connectors port 1 and port 2 as shown in Figure 3.

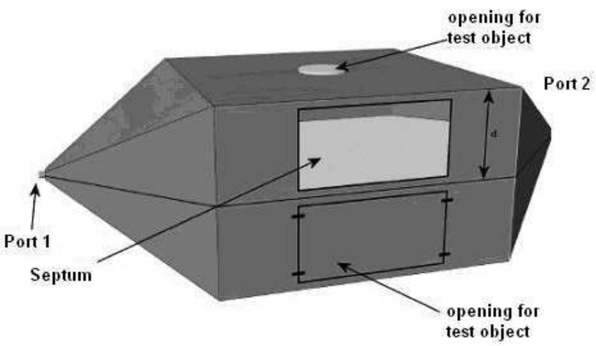


Figure 3: TEM cell: Frequency range DC-950 MHz

Because of the expansion angle, electromagnetic waves propagate through the TEM cell without any reflections. The inner conductor of the coaxial cable extends thereby to a horizontal conducting plate (septum) which divides the cell in middle height. At port 2 of the cell the inner conductor reduces itself to a second coaxial connector. Due to this arrangement, electrical and magnetic fields travel through the cell, homogeneous and perpendicular to the travelling direction. Precondition is a feeding of the cell with alternating current signals or signal pulses at port 1 and attaching terminating impedance at port 2. On the assumption of a linear frequency response of a TEM cell, the homogeneous electrical field strength E inside a TEM cell can be determined as followed:

$$|E| = \frac{\sqrt{P \cdot Z}}{d} \qquad (2)$$

P is the power of the feeding signal, Z the terminating impedance attached at port 2 and d is the distance between septum and the outer conductor of the cell.

Each TEM cell is suitable for a certain frequency range and a maximum feeding power depending on its dimension. With a TEM cell antenna can be investigated about their sensitivity or noise immunity, if the antenna size does not exceed the maximum test volume of the TEM cell.

For verifying the frequency range of the used TEM cell a network analyser was used. Between Port 1 and 2 the TEM cell was installed and the transmission factor S_{12} was measured, see Figure 4.

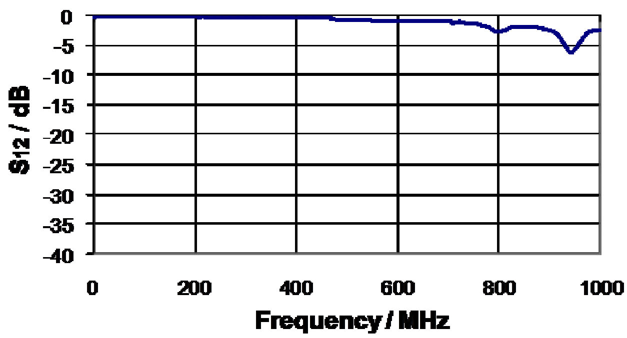


Figure 4: Maximum Frequency of used TEM Cell

Internal reflection of electromagnetic waves causes non-linear behaviour of the transmission factor. The used TEM cell shows a measured linear transmission factor up to 950 MHz and was used to determine the A.F. of the UHF probe in the lower UHF frequency range between 300 and 950 MHz.

2.2. Determining the A.F.

With help of a frequency synthesizer electromagnetic waves with adjustable frequencies propagate inside the TEM cell. By measuring the correlating antenna output voltage the A.F. over the frequency can be determined. To avoid reflections inside the cell, a termination impedance of 50 ohm resistance is attached at port 2. The measurement of the electrical field arising in the place of the antenna is needed for the determination of the A.F., according to (1). For double checking the electromagnetic field inside the TEM cell according to (2) an electromagnetic field probe is used additionally. It offers a precise measurement for the electrical field strength. With the electromagnetic field probe located at the measuring point of the TEM cell and with well-known feeding signals the resulting field strength E(f) is determined in the complete frequency range at the location of the antenna. The measurement set-up for measuring the electromagnetic field strength E(f) follows in Figure 5.

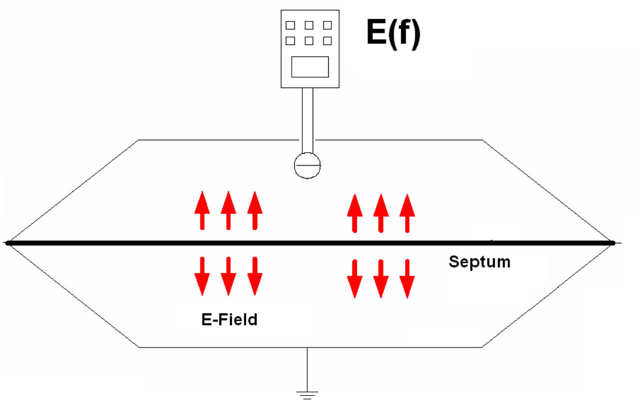


Figure 5: TEM cell measuring E(f)

In case of signals with variable frequency at port 1 it is possible to measure the voltage amplitude of the received signal of any antenna, which is brought into the TEM cell through the suitable opening. The measurement set-up for the determination of the voltage U(f) caused by the receiving electrical field shows Figure 6.

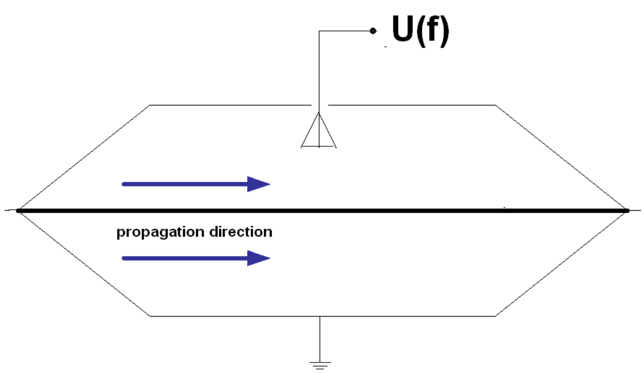


Figure 6: TEM Cell measuring U(f)

The measured frequency characteristics of the electromagnetic field strength E(f) are divided according (1) by the antenna voltage U(f) and results in the A.F. of the antenna, see Figure 7.

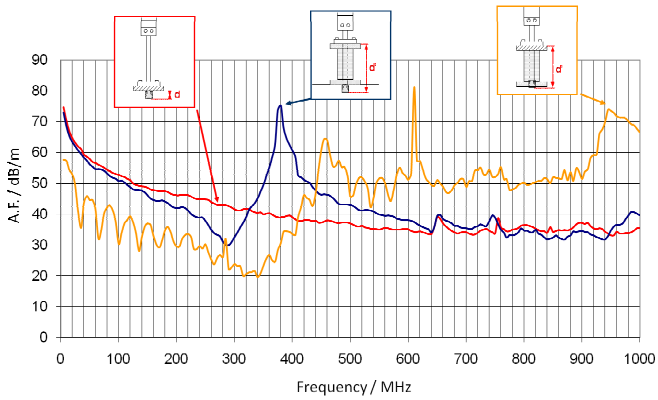


Figure 7: Antenna factors for different probes positions

The three plotted A.F. differ because of the different insertion depth of the UHF PD probes. The different insertion depths base on different measuring arrangements, shown detailed in Figure 8.

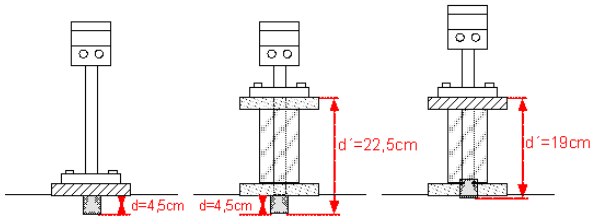


Figure 8: Definition of different insertion depth

First (right arrangement) the Sensor was mounted itself at the opening of the TEM Cell. It represents thereby a monopole above a grounded plate with an length or insertion depth of 4.5 cm. The grounded plate is hereby the probe flange. The correlating A.F. is similar to theory of such monopole arrangements [4]. Probes installed at transformers miss the grounded plate, because the measuring probe head have to be inserted into the transformer tank through a tube, connected to the oil filling valve. In order to measure its influence of that realistic sensor arrangement another sensor arrangements was designed by using a tube with the nominal diameter of 80 mm (DN80), which is often used to connect the standard oil filling valve on power transformers with the tank oil volume. By using that set-up (see Figure 8, middle and right) different insertion depths of the UHF PD probe can be investigated. First (Figure 8, middle) the probe is inserted for 4.5 cm inside the TEM cell, secondly it is nearly plane with the TEM cell outer conductor.

In Figure 7, the two A.F. with use of the tube are more realistic. In the next chapters that arrangement is investigated further. As explained with (1) and Figure 2, the smaller the A.F. the more sensitive the antenna. For frequencies bellow 450 MHz the UHF probe with lower insertion depth is more sensitive, see Figure 7. For frequencies higher than 450 MHz the arrangement of the deeper insertion of the probe is advantageous for higher sensitivity.

Regarding the practical relevance of the measurements one basic influence wasn't taken into account. The TEM cell is filled with air whereas the transformer is normally filled with oil. The influence of oil on the A.F. is investigated in the next chapter.

2.3. Frequency shift by oil

The propagation speed of a electromagnetic wave depends e.g. on the relative permittivity of the surrounding media. UHF PD probes are particularly suitable for measurements in oil-insulating power transformers. Normally electromagnetic waves propagate with the speed of light c_0 which is ideally reached in vacuum. Because of the relative permittivity of oil (ε_r=2,2) the speed of electromagnetic waves in oil V_{oil} is the speed of light divided by the square root of the relative permittivity ε_r of oil:

$$V_{oil} = \frac{C_0}{\sqrt{\varepsilon_r}} \tag{3}$$

The wave propagation speed affects for fixed frequency f the wavelength λ.

$$\lambda = \frac{V_{oil}}{f} \tag{4}$$

The wavelength is due to (4) a function of the propagation speed V_{oil}. Wave based phenomena as antenna readings correlate due to the antenna dimensions to the wavelength λ. In different media the same frequency correlates to different wavelength. For example, a 300 MHz electromagnetic wave has a wavelength of approx. 1 m in air and of approx. 67.4 cm in oil. Due to that the frequency which causes the same antenna reading in air and oil has to be shifted:

$$f_{oil} = \frac{f_{air}}{\sqrt{\varepsilon_r}} \approx 0{,}6742 \cdot f_{air} \tag{5}$$

Due to (5) the A.F. of the UHF PD probe measured in the sections before is affected, because all measurements were accomplished in air. The A.F. is shifted to the lower frequency range when measured in oil than in air.

This is proven in the following with the help of a transition measurement. Two equal UHF PD probes are attached at two sides of a pressure vessel. With the help of a network analyser the transfer function (S_{12}) of the structure was measured in air and secondly filled with oil, see Figure 9. As it is evident, the spectrum of the S_{12}-Parameters shifts to the left in oil in comparison with air.

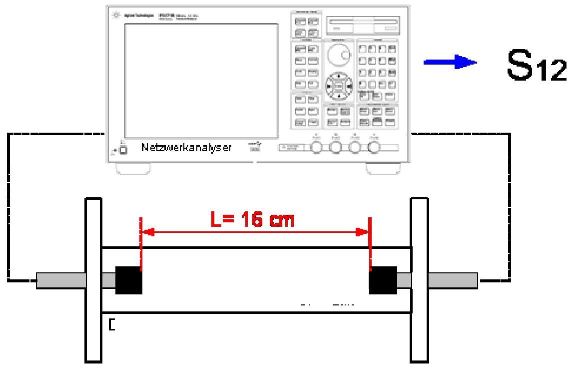


Figure 9: Measuring frequency shift by oil

That is evident due to (5) and could particularly be seen at maxima and minima. For example, with the frequency f_{air}=375 MHz a minimum in the air S_{12}-transition parameter occur, which arises in the oil S_{12}-transition parameter at the frequency f_{oil}=252 MHz. The frequency shift for other minima and maxima, arising in oil, is represented in Figure 10.

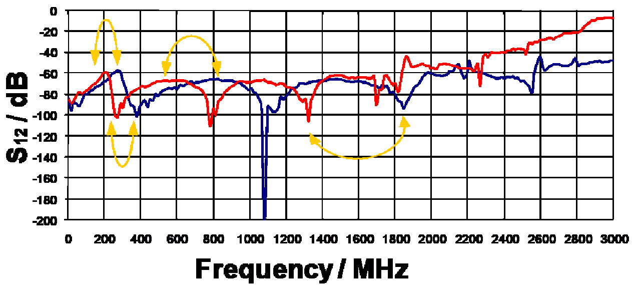


Figure 10: Frequency shift by oil

For certain frequencies the amplitudes of the two S_{12}-parameters differ from each other. The reason might be the amplitude distortion caused by oil [4]. It is to be noted that in air S_{12}-parameter a minimum arises at f= 1070 MHz, which is not to be observed in the oil S_{12}-parameter because of the small dissolution of the network analyser.

2.4. Resulting Antenna Factor

According to chapter 2.3. the measured antenna factor has to be shifted manually to the resulting frequencies due to the surrounding oil. The A.F. of Figure 7 is calculated for oil surrounding in Figure 11, concentrated only on the realistic sensor arrangement with the DN80 tube of the oil filling valve.

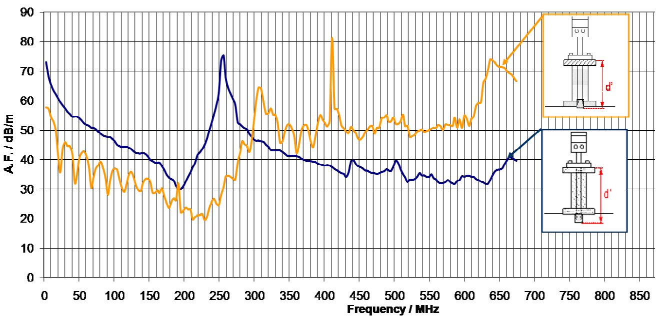


Figure 11: Resulting antenna factor after calculation of frequency shift.

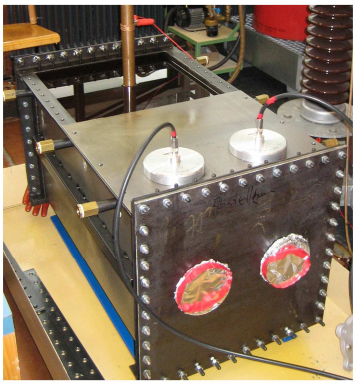
According to (5) the same frequency behaviour is shifted to lower frequencies. In comparison to Figure 7, here at frequency higher than 300 MHz it is advantageous to shift the probe deeper into the transformer. The A.F. is then lower and the antenna is more sensitive for PD emitted electromagnetic waves.

Security reasons limit the maximal insertion depth of the probes because of the decreasing distance to possible conductors inside the transformer at high voltage potential. But in case if the location of the oil filling valve is recognised as not dangerous the inserted probes can achieve a sensitivity much higher than e.g. window coupler attached outside the transformer tank. The findings also allow decreasing the antenna output voltage by pulling the probe head back into the tube. That might be interesting for overdriven measuring units.

3. RADIATION BEHAVIOUR OF PD SOURCES

PD under oil emit electromagnetic waves in the lower UHF range. I.e. occurring wave lengths inside power transformers are between 10 and 70 cm. Regarding antenna theory, an emitting antenna might have the minimum dimension of half the occurring wavelengths to work best, i.e. in the range of 10 cm. That leads to the question, what is the emitting antenna for the PD originated electromagnetic waves? The PD source itself seems to be too small. But PD phenomena cause high frequency currents. Might act some parts of the high voltage structure in the galvanic circuit surrounding the PD source act as an antenna, while high frequency current is flowing through them?

The following set-up was used to examine that question. The so called two-path-arrangement, see Figure 12, offers the possibility to measure independently two UHF signals of one and the same PD impulse.



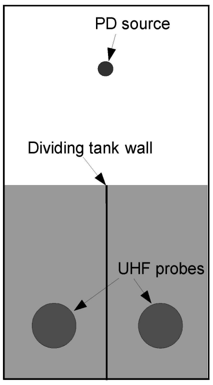


Figure 12: Two-path-arrangement

By a metal wall, two UHF probes are electromagnetically decoupled. The needle sphere PD source inside the two-path-arrangement was energized with high voltage. In the feeding electrode of the PD source a bow of copper was introduced, see Figure 13.

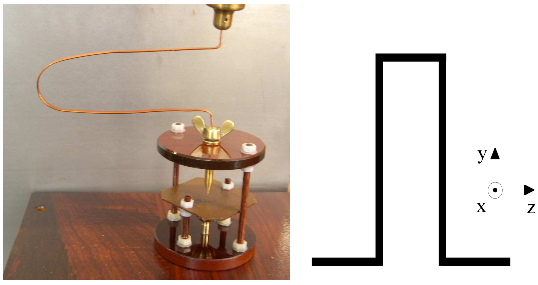


Figure 13: PD source with copper bow as feeding electrode

The high-frequency PD current has to flow through the bow into the PD source. The horizontal dimension of the bow is about 20 cm which leads to a resonance frequency of about 500 MHz in oil.

The two UHF probes have the same range of resonance frequency and measure sensitively the emitted UHF waves. By changing the orientation of the bow, see Figure 14, the qualitative radiation behaviour can be analysed. For each PD phenomena/pulse, the signal energy of the two UHF signals was computed, i.e. E_{left} and E_{right}, see Figure 14. By building the ratio of the two signal energies, the influence of the bow of copper can be estimated. In case of symmetrical paths, the ratio should be 1. In case only the PD source is somehow responsible for the emitted UHF waves (and deviations from slightly changing discharge channels are insignificant), the ratio should remain 1, also in case if changing the orientation of the bow.

In the following the bow was orientated in different positions; see top view in Figure 14.

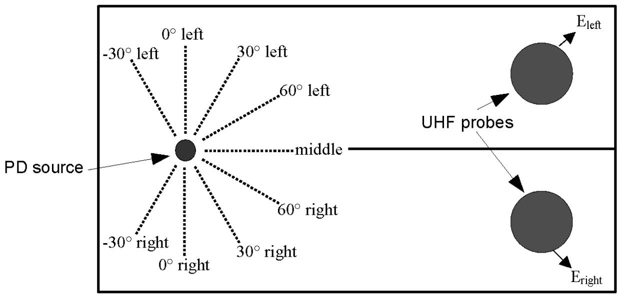


Figure 14: Orientation of the bow in steps of 30°

The PD source was energized with high voltage and produces PD phenomena of 50-100 pC. For each position of the bow, 10 UHF signals for both UHF probes were recorded with a 2 GHz analogue bandwidth transient recorder. Building the ratio of the signal energies between the probe on the left and right side and averaging the ratios leads to the bar diagram in Figure 15.

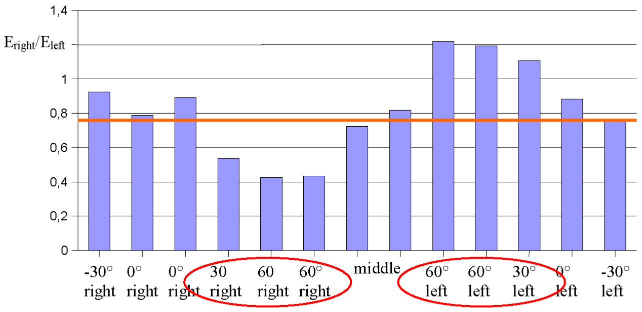


Figure 15: Ratio between measured UHF signal energies with different bow orientations, one bar represents 10 measurements, standard deviation less than 6 %

The orientation of the bow of copper has an influence on measurable UHF signals. E.g. position 30°right shows, that the energy E_{right} must be smaller than the energy E_{left}. That leads to the conclusion, that the bow of copper radiates UHF waves normal to its stretching area, i.e. the diagonal UHF probe receive more energy than the other. Changing the orientation of the bow to the opposite side proofs this radiation behaviour. The standard deviation during all measurements was below 6 %.

The qualitative results of the experiment were proofed in a second step with a simulation tool for high-frequency signals. As could be seen in Figure 13, the bow of copper was modelled with the same dimension as in the measurements. It was energized by a high-frequency current flow (gaussian impulse). The radiation diagram simulated by the software shows the most radiation in normal direction (x-direction) to the stretched area of the bow, see Figure 16.

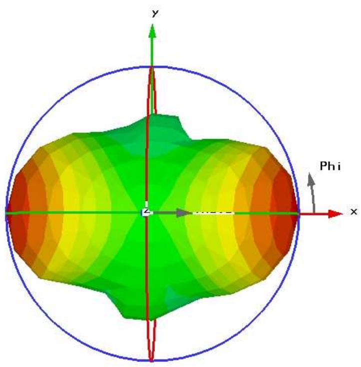


Figure 16: Simulation results of the radiation of the bow

The radiation behaviour of UHF PD sources depends as well on the structure between the high voltage source and the PD source. For future researches it might be useful not only to specify the PD source but rather specify the complete high voltage arrangement.

4. CONCLUSION

PD defects in power transformers can be measured by the emitted electromagnetic field with UHF PD probes. So long those probes are not standardised and measuring results of different probes, often correlating to different research institutes or companies, cannot be compared.

The paper shows a way of characterising the measuring UHF PD probes by their antenna factor. It could be measured realistically in TEM cell under air with an estimation of the influence of the surrounding oil. It is recommended for future to determine the antenna factor for new designed probes as well as for existing and used probes for comparison of measuring results all over the world. Especially in case of frequency analyses the antenna factor should be well known over a broad band of frequencies.

Generally it could be concluded that the sensitivity of the used UHF PD probes for standard oil filling valve depends strongly on the insertion depth. The deeper is the better. That has to be kept in mind in comparison to e.g. external window coupler which might be less sensitive according to the presented background.

Another important aspect for comparison of UHF PD pulses in future is the investigated radiation behaviour of PD. The radiation behaviour of PD might not only be dependent on the PD source itself. In deed the high voltage structure feeding the PD source has some influence. For future researches it might be useful not only specify the PD source but rather specify the complete high voltage arrangement. To adopt the findings in that area to real PD defects in windings or even transformers is task for further research.

5. REFERENCES

[1] IEC 60270 High voltage test techniques – Partial discharge measurement

[2] S. Coenen, S. Tenbohlen, S.M. Markalous, S. Strehl “Sensitivity of UHF PD Measurements in Power Transformers”, IEEE Transactions on Dielectrics and Electrical Insulation, Vol. 15, No. 6, pp. 1553-1558

[3] M. Judd, “Partial Discharge Monitoring for power transformers using UHF sensors”, IEEE Electrical Insulation Magazine Volume 21, Issue 3, 2005

[4] C. A. Balainis, “Antenna Theory”, 3. Editon, Hoboken, N.J.: Wiley-Interscience, 2005

[5] S. Coenen, S. Tenbohlen, S. M. Markalous, T. Strehl: “Performance Check and Sensitivity Verification for UHF PD Measurements on Power Transformers”, Proceedings 15th ISH, Paper-No: T7-100, Ljubljana, Slovenia, 2007