Influence of PD Location in Transformer windings on IEC60270- and UHF-Measurements

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***Abstract*— The reliability of electrical power systems depends 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 destroying events power transformers are e.g. tested on partial discharge (PD) activity before commissioning and currently also during service.**

As there are different PD measurement methods, that thesis deals with the influence of PD location on the measurement results. A movable PD source is presented, which is movable over the entire height of a high voltage winding and generates PDs along the inner surface. The influence of different heights inside the winding on two different PD measurement systems is presented: The electrical method according IEC60270 and the UHF PD measuring method. The electrical method measures in terms of picoCouloumb (pC) the apparent charge with the help of a coupling capacitor in frequency range below 1 MHz. The UHF-Method with a bandwidth from 300 MHz up to 3 GHz bases on emitted electromagnetic waves which are measurable with e.g. oil valve sensors inside the transformer tank.

Although a calibration process according to IEC60270 is performed, the measurable apparent charge strongly depends on the PD source location within the winding, whereas the emitted UHF waves are less affected by the PD source location. The reliability of electrical power systems depends 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 destroying events power transformers are e.g. tested on partial discharge (PD) activity before commissioning and currently also during service.

Keywords -- Power transformer, partial discharges, ultra high frequency, UHF method, PD pattern, Apparent Charge, IEC60270

I. INTRODUCTION

The reliability of electrical power systems depends on the quality and availability of electrical equipment like power transformers. Examining existing insulation quality of oil/paper-insulated transformers during full operation or at least in the field gets more and more important because of the increasing number of transformers reaching their technical life expectancy. Local failures inside their insulation may lead to catastrophic breakdowns and might cause high outage and penalty costs. To prevent these destructive events power transformers are e.g. tested for partial discharges (PD) activity before commissioning and currently also during service.

The conventional measurement of the apparent charge of PD according to IEC60270 [1] and signal decoupling with a high voltage capacitor are common measurement technology for quality assurance of high voltage (HV) equipment. According to IEC60270 the measurement setup can be calibrated in terms of pico Coulomb (pC). The measurable so called apparent charge in terms of pC miss a direct correlation to the charge exchange within the PD. Although threshold values of the apparent charge levels for acceptance test after manufacturing of new power transformers proofed to be successful since recent years.

Performing the same calibration process in field, PD measurements on-site should have the same sensitivity in terms of pC. But no standardized threshold values of the apparent charge for aged transformers tested again on PD activity in field are valid or at least accepted. The declaration of insulation condition is endlessly discussed in case of any measured PD activity.

Because of an integral calculation of the apparent charge, the normal IEC60270 measurements supposed to be independent of measurement setup and the location of the PD source at least after calibration. The current paper deals with that misunderstanding of the IEC60270 measurements and gives further proof, that focusing only on the apparent charge is not helpful, because measurable apparent charge depends on the normally unknown location of the PD source at the winding.

In recent years a growing demand for on-site/on-line PD diagnostics with high measurement sensitivity led to the development of innovative advanced PD decoupling and measurement methods to overcome certain drawbacks of the conventional method in these applications. Combining the so-called UHF (Ultra High Frequencies) or acoustic sensor technology with suitable instrumentation and data processing gives a series of advantages for different HV devices as:

- Separation of internal and external PD signals (“Faraday’s cage/shielding” effect of the transformer tank for UHF detection)
- Diagnostic double checks and possibly deeper insight in deterioration processes e.g. through comparison with IEC60270 measurement results
- Geometric PD location (either by a combination of UHF and acoustic method or the sole application of one of the methods depending on devices under test)

PDs under oil are very fast electrical processes and radiate electromagnetic waves with frequencies up to the ultrahigh range (UHF: 300 – 3000 MHz). The current contribution deals additionally with the electromagnetic method, also known as the UHF-Method. The emitted electromagnetic waves are less affected by the measuring setup and the PD source location.

II. MOVABLE PD SOURCE WITH CONSTANT GEOMETRY AND MEASURING SET-UP

Main part of the PD source is a typical HV disc winding, as used in oil-insulated transformers. The winding is on high voltage potential and not grounded, i.e. that each turn is on the same potential. For that arrangement the winding is free of PD up to a measurement voltage of 35 kV. For the generation of PD a grounded metal sheet core is fit into the winding. That sheet consists of a bearing, which allows moving an aluminum cube over its entire height. Therefore the cube is mounted on a threaded control rod, which changes the position of that cube by being rotated, see Figure 1.

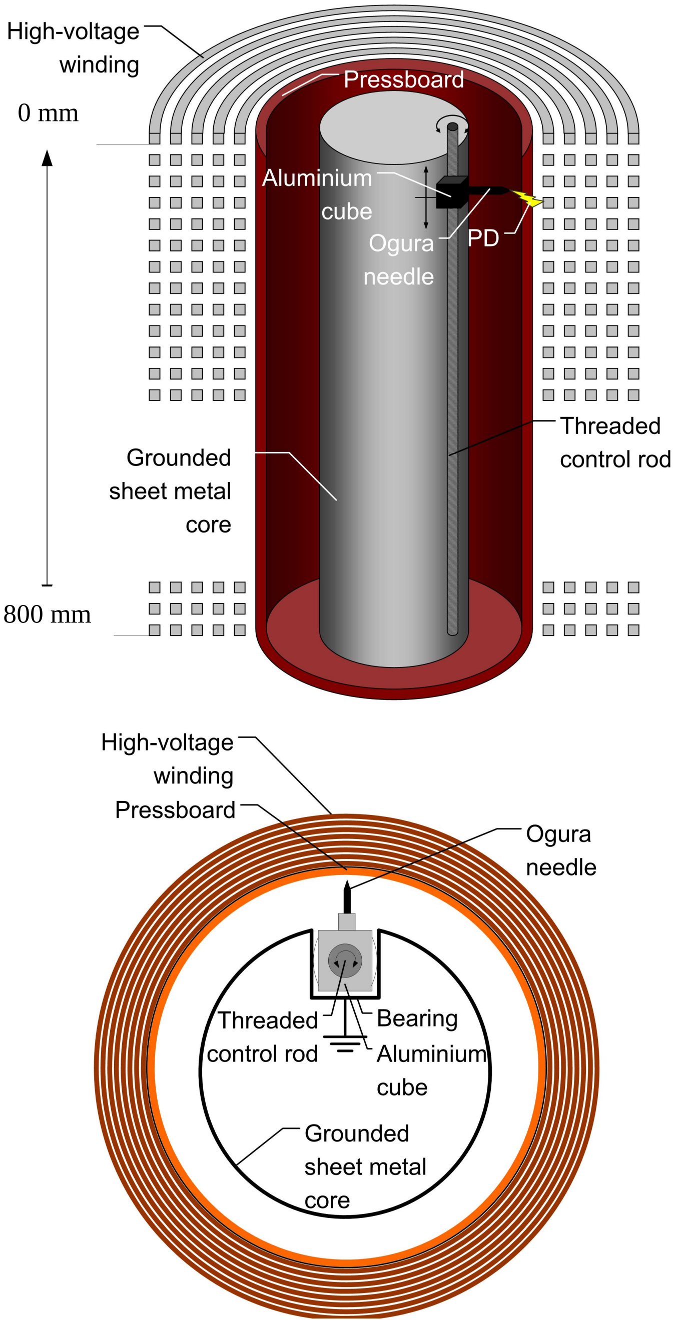

Figure 1. Sketch of the PD source construction inside a high voltage disc winding: top) vertical view, bottom) top view

Mechanical conditions of the winding lead to possible locations of the PD source within the winding of 0 mm - 800 mm. A stated PD source location of 0 mm indicates the highest possible position within the winding, whereas a stated value of 800 mm implies that the PD source is at the bottom of the winding. An Ogura needle [2] is mounted on that moveable cube perpendicularly to the surface of the grounded sheet core. At the tip of the grounded needle (tip radius $r_p = 3$ µm) occurs a field enhancement of the electric field, when the winding is connected to high-voltage potential. That field enhancement leads to the generation of PD (inner corona) at measurement voltages of higher than 25 kV. Thus it is possible to generate PD along the inner surface of a high-voltage winding over its entire height, without changing the electrode geometry of the PD source.

By changing the PD source location there is no change in its geometry, but there is a significant change in the impedance between the PD and the voltage supply. Each single winding consist of a series inductance L_S, parallel capacities to the tank surface and sheet core (concentrated to C_A) and capacities to the other windings (C_W), see Figure 2.

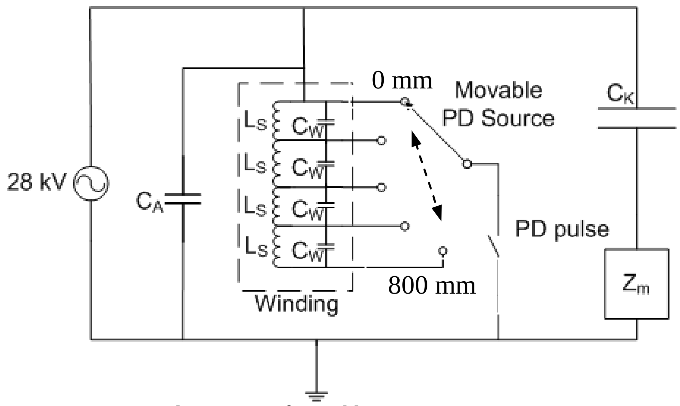

Figure 2. Equivalent circuit of movable PD source

At the highest position of the PD source, e.g. 0 mm, the series inductivity (L_S) is at its lowest value. At the moment of a PD, represented by the switch in Figure 2, its discharge current (sourced by C_A and C_K) flows through a parallel circuit of L_S and C_W. At a PD source position lower in the winding, e.g. 800 mm, the discharge current has to flow through a series network consisting of a number of parallel circuits of L_S and C_W. The series inductances are added linearly, whereas the sum of the winding capacities decreases in value. Thus the high-voltage winding has a filtering effect on the PD discharge current and influences the results of electrical PD measuring systems which will be presented in the next chapters.

The HV winding, including the PD source, is placed into a cylindrical transformer tank, which is filled with mineral oil. The tank ground is connected to the metal sheet core and both grounded via copper bands to the main ground. The HV winding is connected to a HV AC source and a parallel coupling capacitor ($C_K = 2.5$ nF) according to the test circuit stated in IEC60270. There is a coupling quadruple (Z_m) inserted between the low potential side of the coupling capacitor C_K and its grounding. That quadrupole has two output ports, one to measure the test voltage and another to detect PD. That PD-output has according to IEC60270 a band-pass behavior within the range of 15 kHz to 15 MHz.

The calibration process according IEC60270 was performed by injecting calibration pulses at the top of the winding outside the tank. A change in the PD source position did not influence the value of the recorded calibration factor.

Two DN80 flanges of the used transformer tank allow the installation of two UHF-sensors [3]. These sensors detect the electromagnetic emissions of occurring PD, without influencing the electric measurement circuit of IEC60270.

III. CHANGE OF APPARENT CHARGE DEPENDING ON PD LOCATION

Figure 3 shows the PRPD pattern of four PD source positions, 0 mm, 100 mm, 200 mm and 500 mm. The electrical PD measurements resulting in these patterns, were performed at test voltages of 28 kV, using a commercially available PD measurement system, evaluating the PD currents in a frequency band of 3.5-4.5 MHz. That is due to IEC60270 because the readings do not differ from those as monitored for the recommended values of the frequency band [1].

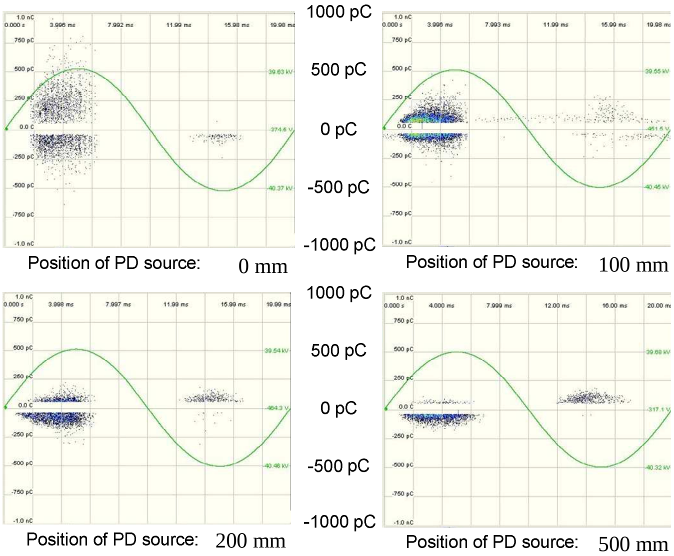

Figure 3. PRPD pattern at test voltages of 28 kV and changing height of PD source locations

The detected PDs remain constant in terms of phase angle, but decrease in amplitude in terms of pC by decreasing height of the PD source. E.g. at a source position of 0 mm the recorded PD have maximum amplitude of about 900 pC, decreasing to 100 pC maximum at a source position of 500 mm (PD of first phase quadrant). All measurements were performed at test voltages of 28 kV.

Additionally a change in polarity can be observed: The recorded PDs at a position of 0 mm have higher magnitudes in the first phase quadrant as in the third. In the first quadrant the magnitudes of the positively charged PD exceed the ones of the negatively charged PD. The PD of the third quadrant are mainly of negative charge. At a PD source location of 500 mm this fact changes to mainly negative charges in the first quadrant and positive in the third.

That possibly leads to problems in the pattern analysis, as the PRPD pattern of a source location of 0 mm indicate a high field enhancement at a grounded tip (inner corona)[4]. The pattern originating from the same PD source at a position of 500 mm contrarily fit rather to inner corona of a high potential tip, with lower electrical field strength. As the geometry of the PD source does not change, there should be no change in the real charge over the source location.

The IEC60270 setup cannot resolve if the change of measurable apparent charge bases on change of the PD source pulses or on changing impedance in the measurement circuit. Simultaneously measured UHF signals indicated that the PD pulses of the PD source stayed constant over the entire height, because the UHF radiation of the PD source didn´t change significantly, see chapter IV. Due to that the changed impedance, as explained with Figure 2, causes the filtering or damping effect of the measurable apparent charge of the PD source.

Calibration procedure is not able to adopt with that phenomena because calibration pulses are only injectable outside the winding, e.g. on the bushings of transformers. The changing winding impedance by changing PD localization is not taken into account and even the idea to deal with that phenomenon by integration of the current impulse of PD seems not workable.

The presented results are dependent on the measuring frequency band, i.e. the damping effect of the winding depends on the measuring frequency range. Not all recommended frequency ranges in IEC60270 seems to have the same sensitivity and further investigations will focus on that and will be published.

To verify the change of apparent charge depending on the PD location, ultra-wide-band measurements with oscilloscopes are performed and presented in the next chapter.

IV. COMBINED UHF AND IEC MEASUREMENTS

A combined measurement setup allows a comparison of the measured apparent charge with the electromagnetic radiation of a PD. Investigations [3] demonstrate a high sensitivity of UHF measurements by means of low attenuation factors caused by e.g. windings and structures of the active part of transformers.

Three oscilloscopes are synchronized via trigger input/output. One oscilloscope records the time domain IEC signal of a PD at the PD output of the coupling quadrupole. The apparent charge is calculated after IEC calibration process by taking the peak value of the pulse, [5]. That oscilloscope triggers two additional oscilloscopes, one to measure the radiated UHF emissions in time-domain and one to log the test voltage at the voltage output of the coupling quadrupole, see Figure 4.

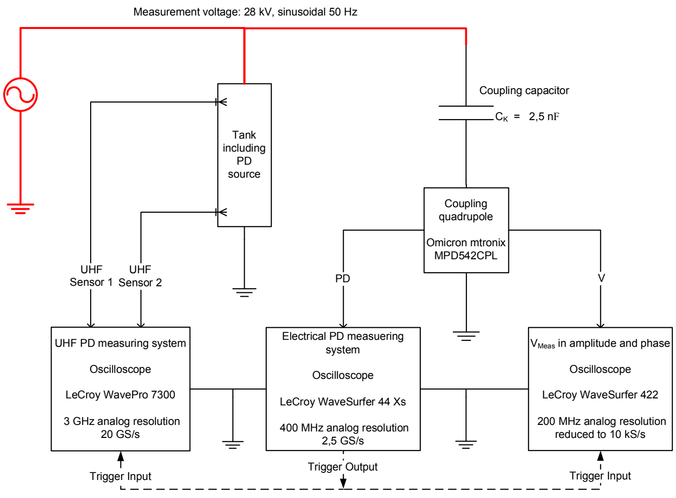

Figure 4. Test setup for combined oscilloscope measurements

That test setup results in comparable PRPD patterns as shown in Figure 3 and thus the behavior of the apparent charge depending on the PD source location is validated.

Figure 5 shows the comparison of the apparent charge of a PD with its UHF radiation at three PD source positions. In that figure the apparent charge is plotted on the x-axis and the maximum of the output voltage at UHF sensor 1 (max(|VUHF|)) is plotted on the y-axis at positions of 0 mm, 150 mm and 500 mm.

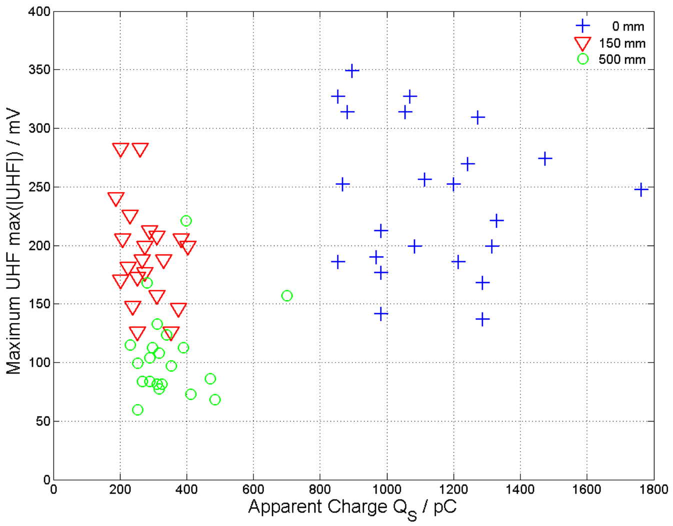

Figure 5. Apparent charge plotted versus UHF radiation at different PD source locations

It shows that PD at a source position of 0 mm have an apparent charge of 800 – 1800 pC and a maximum UHF amplitude of 140 – 350 mV. At a source position of 150 mm the apparent charge is decreased to values of 200 – 400 pC with maximum UHF amplitudes of 120 – 300 mV. Compared to each other, the apparent charge decreases by a factor of 3, whereas the UHF amplitude decreases only by a factor of 1.2.

The apparent charge of a PD decreases far more by decreasing height of the source position within a high-voltage winding than its UHF radiation. The small attenuation of the UHF waves was demonstrated [3] and explains the decreasing UHF signal amplitude by higher distances between PD source and UHF Sensor. I.e. the radiation behavior of the PD source stays nearly constant over the changing height. That was further proofed by simultaneously measured acoustic signals for localization purpose [6] which additionally proofed that the Ogura needle was the only active PD source inside the tank. By that it can be concluded, that the measurable apparent charge must be changed by the influence of the changing winding impedance due to changing PD height, see Figure 2, whereas the real charge of the PD itself might stay the same due to the constant electrode geometric.

V. Conclusion

A movable PD source inside a high voltage winding allows measuring the influence of PD location on PD measurement results. The test results show a high damping and polarity changing effect of the winding on the apparent charge, measured with test circuits according to IEC 60270.

Measured apparent charge is dependent on the PD localization inside the winding. That effect was proofed with a commercial PD measurement system as well as with a measuring setup based on measured raw data.

Parallel UHF measurements indicate that these effects do not resolve on changing PD source properties, but on filtering effect of the winding impedance on the discharge current of PD.

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