

# Comparison between Electrical and UHF PD Measurement concerning Calibration and Sensitivity for Power Transformers

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**Abstract**— The application of regular condition checks and continuous monitoring of power transformers gains in importance. Nowadays, these methods are frequently used to detect damages in the insulation system at early stage and thus to avoid outages. In addition to the electrical partial discharge (PD) measurement according IEC 60270 [1], the electromagnetic measurement method starts to become common practice. It is suitable for diagnostic measurement on-site and also as continuous PD monitoring system because of its lower sensitivity to external interference compared with the electrical measurement. For electrical PD measurement a calibration procedure for the ratio between capacitance of specimen and coupling capacitor is available. Although the actual PD charge still remains unknown, the associated comparability of electrical PD measurement systems has led to an acceptance level at transformer routine tests. A similar calibration of the electromagnetic UHF (ultra-high frequency: 300 MHz – 3 GHz) measurement has not been implemented yet, but is a necessity for further standardization of this method. This contribution compares both methods and takes a critical look at the established PD acceptance level. Therefore, the diagnostic value of the apparent charge measured according to IEC 60270 is discussed with regard to its dependency on the propagation path inside the winding and the frequency range of the measurement.

**Keywords**—*Partial Discharge (PD), Power Transformer, Sensitivity, Calibration, UHF, Apparent Charge*

## I. INTRODUCTION

PD measurement is suitable to detect damages in the insulation of power transformers at an early stage and thereby helps minimizing the risk of failure. In addition to the conventional PD measurement according to IEC 60270 [1], which determines the electric charge of PD, the electromagnetic measurement method becomes increasingly important. The electromagnetic emission of a PD is measured using an UHF antenna which is inserted into the transformer tank. Due to the Farady shielding of the transformer tank [2], [3], [4] and the filter function of high voltage bushings this method is less sensitive to external interferences compared to the electrical method and therefore also suitable for measurements in noisy environments, e.g. for onsite / online measurements and monitoring. Since PD detection and location techniques are still evolving, the Cigre Working Group WG A2-27 recommends in brochure 343 to provide DN50 valves for the later fitting of UHF probes as valves provides the greatest flexibility for the future. Alternatively, dielectric windows can be provided for UHF sensors [5].

Besides the apparent charge which is defined by the integrated recharging current through a coupling capacitor or a current probe and the electromagnetic radiation, PD also emit acoustic signals and ultra violet light. In addition, PD produces fault gases by chemical processes which dissolve in the surrounding insulation oil. Optical detection of PD is in principle not applied for PD in transformers. The acoustic measurement is mostly used for localization of PD using time differences [6], [7].

Since the UHF method is applied in increasing numbers, the question about its calibration raises. Calibration is necessary to achieve comparability of UHF measurements, like in the conventional method. Often, calibration of UHF sensors is used as a synonym for relation the between measured UHF antenna voltage (in mV) and apparent charge (in pC) of the electrical measurement. Several publications state this connection as non-existent for complex structures like power transformers [8]. For this reason, a general consideration of calibration methods for UHF and electrical measurements are determined and compared on the following pages. Therefore, the signal paths of both measurements are evaluated considering mainly two points:

- 1) Which part of the signal path can actually be included in the calibration and does not unknowingly influence the measured outcome?
- 2) Which parts are not included and what factors do influence those parts?

## II. ACTUAL PD LEVEL

The fundamental difference between the two measurement methods is the physical value. The apparent charge level of the electrical measurement is determined by integration of the recharging current. For UHF the electromagnetic radiation of the PD is measured using antennas. Because both methods cannot measure directly at the defect site, the actual level of PD (pC or mV) remains unknown in a power transformer. A calibration can only include the signal path between the signal recorder and the connection point of the sensor to the transformer. For the electrical measurement the connection point is the bushing. For PD signals near to the calibration point (e.g. at the lead exit) actual and apparent charge are similar. PD signals which originate farther from the calibration point are influenced by the propagation path. This path is not exactly known and cannot be calibrated. In principle, the same applies for the UHF method, but with a different propagation path. Also, in the UHF measurement PD can be measured in

the direct vicinity of the sensor with nearly its actual signal level. With distant sources, the electromagnetic waves pass through an unknown complex system before they can be measured at the sensor. A conclusion cannot be drawn between the measured signal and the actually converted energy at the fault by both measurement methods. Therefore, it is difficult to make a statement whether there is a critical or tolerable fault only by the measured PD level with both measurement methods.

A linear correlation between apparent charge and the antenna voltage can be demonstrated in a constant laboratory setup but not for complex structures [8]. Both measured variables theoretically contain the same information. From laboratory experiments, a rough estimation can be derived: several 10 mV UHF signal corresponding to several 100 pC apparent charge. However, some PD sources do not radiate in the UHF range and can only be measured conventionally. On the other hand, electrical signals from PD that are located deep in the winding, are strongly damped and lead to very small apparent charges at the measuring point which can be below noise level.

### III. ATTENUATION IN THE PROPAGATION PATH

The propagation mechanisms of electrical and electromagnetic measurements are fundamentally different and so are the attenuations of the signals. In the electrical PD measurement the winding conductor serves as propagation path. Also, the winding represents a RLC network with low-pass filter function [9], [10], see Fig. 1.

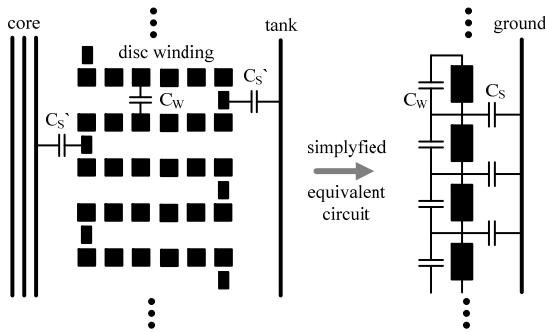


Fig. 1 Transformer disc winding as filter for electrical PD signals

In addition, the internal capacities at fault location are unknown at the fault location. This can be shown by a void inside the insulation system. In Fig. 2 a simplified void is shown with surrounding intact insulation system. If a PD occurs, the capacity  $C_1$  of the void is partially recharged from the inner capacities  $C_3'$  and partly from the external coupling capacitor. Only the recharging current of the connected coupling capacitor can be measured. Since both the location and the dimension of the defect are not known, the ratio between the capacitances  $C_1$ ,  $C_2'$  and  $C_3'$  is not known and so the internal recharging current.

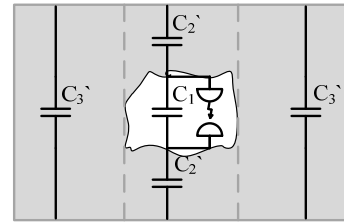


Fig. 2 Internal capacitances of a void ( $C_1$ ), and of the surrounding insulation material ( $C_2'$  and  $C_3'$ )

The propagation of the electromagnetic signals in the UHF range is not galvanically in the winding but in the entire volume of the transformer, in oil and pressboard. Thereby, the electromagnetic wave is attenuated and can be reflected at metallic parts. The attenuation of the electromagnetic propagation inside a transformer is relatively low. It is approximately 2 dB per meter for transformer oil [8].

### IV. PROOF OF SENSITIVITY

In the electrical PD measurement a calibration pulse can be fed to the bushings or the coupling capacitor, not directly into the winding. Thus, the propagation path in the transformer is not taken into account and the measurement sensitivity for PD inside the winding is not calibrated.

In the electromagnetic measurements a UHF pulse can be fed to one sensor and measured by another if two or more sensors can be applied to the transformer. If the sensors are on opposing sides of the transformer as shown in Fig 3, the sensitivity test includes the entire signal path through the transformer [11], [12]. However, it is not possible to inject a UHF pulse directly in the winding and the sensitivity for PD directly in windings can not be determined, too.

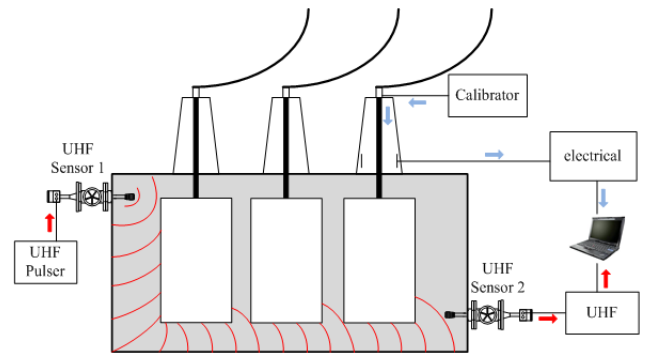


Fig. 3 Sensitivity check of electrical and electromagnetic PD measurement

### V. CALIBRATION OF ELECTRICAL METHOD

By feeding in a known charge pulse  $q_0$  as close to the device under test (DUT) as possible, the ratio of the measurable charge  $q_m$  to the apparent charge  $q_s$  is determined and adjusted by a calibration factor. By calibration the ratio of coupling capacitance  $C_K$  and the capacitance of the DUT  $C_T$  is determined and compensated. Fig. 4 illustrates a typical PD measuring circuit consisting of DUT, coupling capacitance, quadruple, PD measuring system and calibrator.

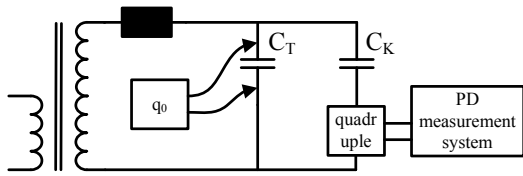


Fig. 4 Calibration of electrical PD measurement

Although calibration does not provide the knowledge of the actually converted charge level, a common acceptance level for the apparent charge  $q_s$ , has become widely accepted, especially in factory routine tests [13]. The value of the apparent charge can be related to the actual charge considering simple propagation paths like cables. This value is less meaningful in electrically complex equipment such as power transformers [14].

## VI. INFLUENCE OF PD LOCATION AND FREQUENCY RANGE ON THE APPARENT CHARGE

The influence of the location of the PD on its electrical signals is determined using a laboratory setup. A cylindrical steel tank is equipped with a winding and an artificial PD source which is adjustable in height. The winding is on high voltage potential, the lower winding exit is not connected to ground. Fig. 5 shows the experimental setup.

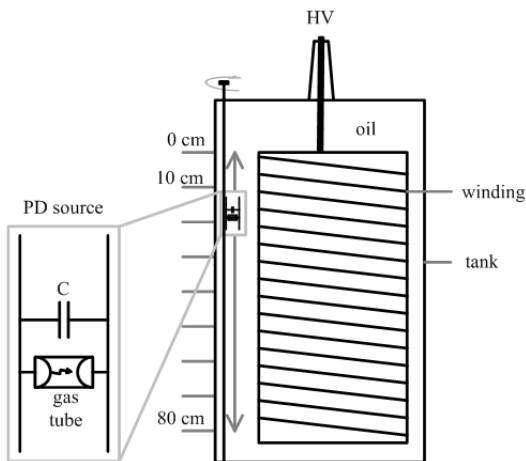


Fig. 5 Laboratory setup with artificial movable PD source

The artificial PD source is connected to ground on one side and consists of two copper plates connected through a capacitor and a gas-filled discharge tube (GDT). It is used because it provides a reproducible, phase stable, constant charge conversion. The constant charge is given by the product of the capacity and the constant response voltage of the GDT, neglecting side effects. The PD source is fixed on a threaded rod which can be adjusted in height along the winding. Fig. 6 shows a phase resolved partial discharge pattern (PRPD) and the constant level of the source over time (trend).

The PRPD in Fig. 6 shows two single phase stable discharges at a constant level and the corresponding trend. In the trend first the voltage is held above PD threshold voltage for about one hour, and thereafter the PD source is turned off and on again by changing the voltage, so the reproducibility of the artificial PD source is acknowledged.

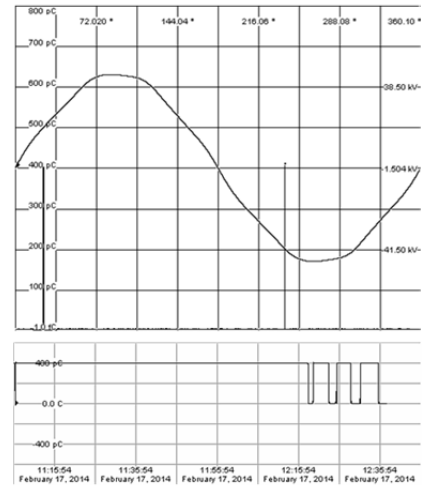


Fig. 6 PRPD and trend of stable artificial PD source

With this PD source a broadband electrical PD measurement is performed on the experimental setup shown in Fig. 5. The upper frequency limit of the used quadrupole is about 15 MHz. The voltage signal at the output of the quadrupole is proportional to the recharging current. Its time domain signal is converted into the amplitude density spectrum in frequency domain using Fast Fourier Transformation. Fig. 7 shows the amplitude density spectrum at four different PD positions along the winding.

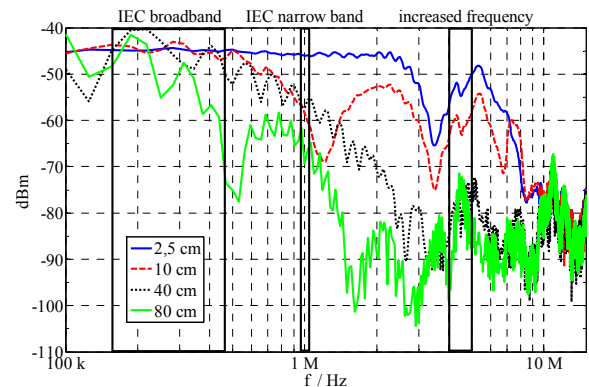


Fig. 7 Amplitude density spectrum of electrical measurements at different PD locations along the winding

An increasing damping due to the low-pass filter effect of the winding with increasing insertion depth of the PD source can be recognized. Highlighted are three frequency ranges. It is measured conforming IEC 60270 wideband and narrowband respectively. The third range at increased frequency is not IEC conform but often used at on-site PD measurements in order to suppress external interferences.

The used frequency ranges are:

- IEC broadband:  $f_m = 300 \text{ kHz}$ ,  $\Delta f = 300 \text{ kHz}$
- IEC narrowband:  $f_m = 1 \text{ MHz}$ ,  $\Delta f = 30 \text{ kHz}$
- Increased Frequency range:  $f_m = 4.5 \text{ MHz}$ ,  $\Delta f = 1 \text{ MHz}$

In Fig. 8 the apparent charge is measured in this three frequency ranges to see the damping effect on the PD position along the winding. The PD measurement system is recalibrated after each change of the frequency range.

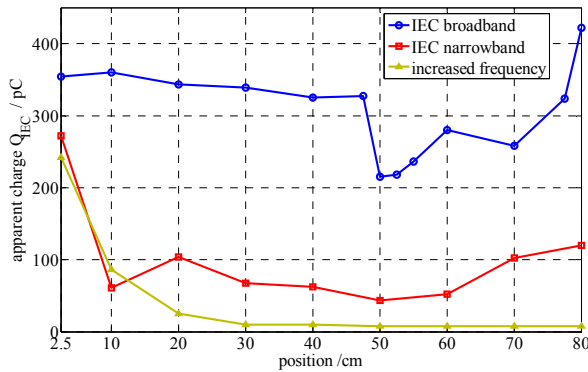


Fig. 8 Apparent charge depending on PD position along the winding and depending on the measured frequency range

Despite calibration and a reproducible, stable PD source significantly different PD levels are measured even at low insertion depths due to the filter effect of the winding. Using wide-band frequency range, a strong decrease in the level at 50 cm by app. 140 pC can be seen, which could be initially assumed to be a measurement error, but is confirmed by an increased number of measurement points at similar insertion depth. Especially the measurement in the increased frequency range ( $f_m = 4.5$  MHz,  $\Delta f = 1$  MHz) shows that starting with a PD position of about 30 cm a signal is hardly measurable. Thus, this frequency range not only suppresses interferences at on-site measurements, but also suppresses the measurement of PD in the winding strongly. This effect will be even more pronounced in case of larger windings.

## VII. CONCLUSION

In Table 1 a compilation of the influences on the calibration capability of the two measurement methods is listed.

TABLE I. COMPARISON OF ELECTRICAL WITH ELECTROMAGNETICAL PD MEASUREMENT METHOD

	IEC 60270		UHF	
	pC	not known	mV	not known
<b>Actual PD source level</b>	pC	not known	mV	not known
<b>Attenuation in coupling path</b>	low pass filter & internal capacitance ratio	not known	damping of EM waves	not known (but low)
<b>Sensor sensitivity</b>	ratio of coupling capacitor to DUT capacitance	calibrated	antenna factor	not yet calibrated
<b>Acceptance level</b>	<100 pC	@ 1,2U <sub>N</sub>	?	?

If the calibration capabilities of electrical and electromagnetic PD measurement methods are compared, unknowns in the signal path remain unavoidable in both cases. The advantage of the electrical to the electromagnetic measurement is its calibration up to the connection point to the power transformer. However, the signal propagation inside the transformer remains unknown. Therefore the measured, apparent charge gives just an indication of the actual charge or energy conversion of the PD source inside the winding. Calibration of the UHF method is not available yet, but possible. This can be done by characterization of the UHF sensor using its antenna factor. This is essential to allow a standardization of the electromagnetic UHF method and to define acceptance levels.

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