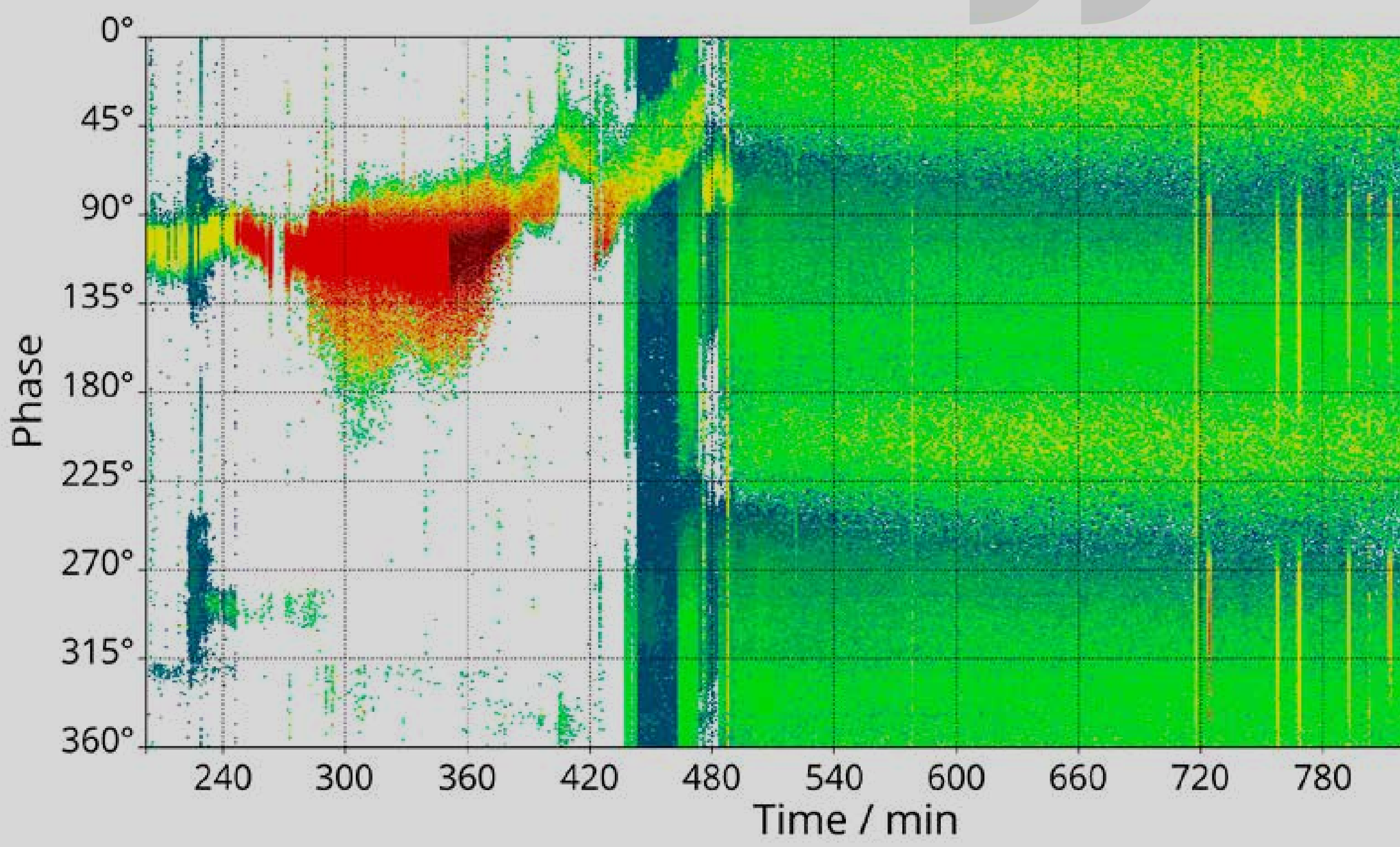
PD measurement is suitable to detect damages in the insulation of power transformers at an early stage which helps minimising the risk of failure



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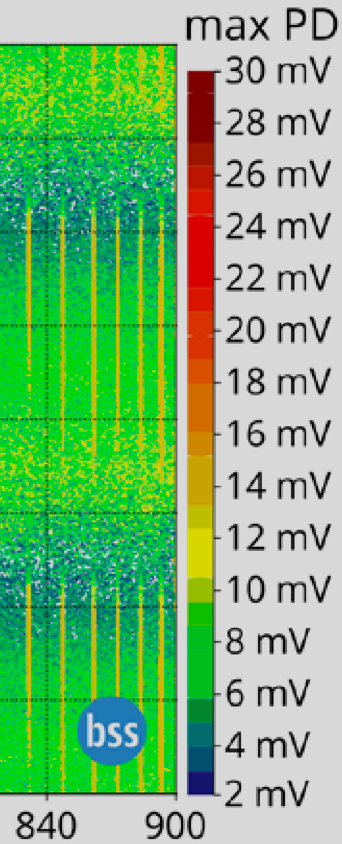
Partial discharge monitoring of power transformers by UHF sensors

ABSTRACT

Electrical energy networks' reliability is driven by both the quality and the reliability of its electrical equipment, e.g., power transformers. Local failures inside their oil / paper insulation can cause a breakdown resulting in major outage and penalty costs. Power transformers are tested on partial discharge (PD) activity at a factory routine test. In addition, UHF PD monitoring can be used to prevent harmful events during service. Therefore, continuous monitoring can be beneficial compared to singular diagnostic measurements; diagnostic PD measurements provide snapshot information which lacks trend information. Also, temporary measurements can cause misleading interpretations due to the volatile nature of PD. UHF PD monitoring systems can be calibrated for comparability in a two-step procedure, including the sensor characteristic. UHF sensor positions must be selected for good coverage of the active part, high sensitivity, and safety reasons.

KEYWORDS

power transformer condition assessment, UHF PD calibration, UHF PD monitoring, UHF sensor positioning



The electromagnetic UHF method is often used for on-site diagnostics, because of its higher signal-to-noise ratio; the electromagnetic emissions of PD are recorded using a UHF antenna which is installed into the transformer tank

1. Introduction

Power transformers are essential to the reliability of the electrical grid. Hence, the reliable operation of power transformers is vital for supply security. Transformer failures regularly lead to significant damage and associated costs. All critical internal faults should be detected at first appearance. Therefore, different diagnostic methods have been developed to meet the increasing demands for on- and off-site measurements [1]. In particular, partial discharges (PD) measurement has been established to detect local defects in the paper / oil insulation. Defects can be both initiated and subsequently enlarged by the destructive nature of PD.

There are three different ways of PD monitoring: indirect detection by dissolved gas analysis (DGA) and direct detection by either electrical PD measurements according to IEC 60270 [2], or by electromagnetic measurements in the ultra-high frequency range (UHF: 300 MHz – 3 GHz) [3]. DGA only provides an indication of the presence of PD. An increasing number of transformers are monitored using direct methods. PD measurement is suitable to detect damages in the insulation of power transformers at an early stage and thereby helps minimising the risk of failure [4]. Its significance is emphasised by a standardised electrical measurement according to IEC 60270, which is required for all acceptance certificates at routine testing. The apparent charge Q_{IEC} is an indicator of transformer quality. The electromagnetic UHF method gains importance in terms of monitoring and on-site diagnostics [5]. The electromagnetic emissions of PD are recorded using a UHF antenna which is installed into the transformer tank. The principle propagation paths of the methods are shown in Fig. 1.

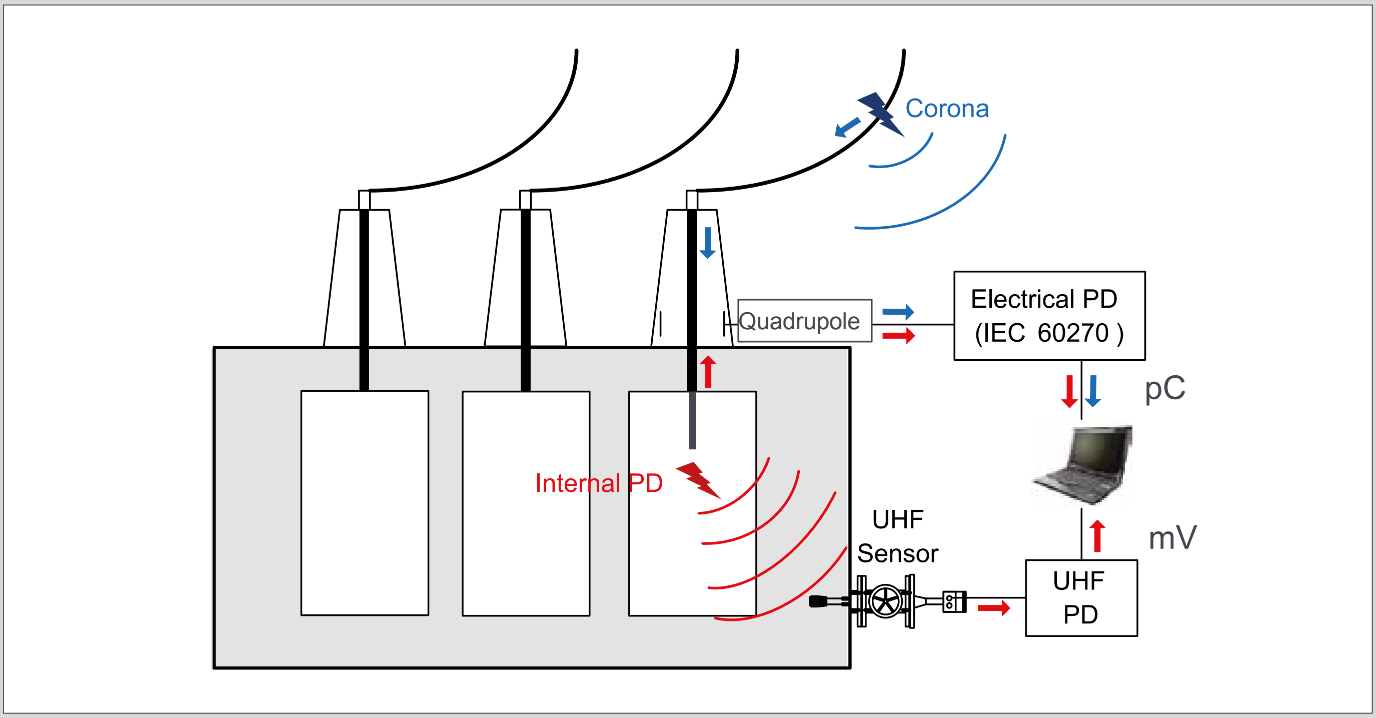


Figure 1. Signal propagation of UHF and electrical PD measurement at a power transformer with internal PD (red) and external PD (blue) [6]

A UHF sensor consists of a broadband antenna optimised for the UHF frequency range radiated by PD, and of its mechanical adaption for the installation on power transformers

Electrical signals propagate by the galvanic coupling of the winding and are decoupled by the measurement capacity of the bushing for online monitoring or with an external coupling capacitor (not shown). Electromagnetic signals travel directly through the oil-filled volume of the transformer. Usually, the Faraday shielding of the transformer tank and low-pass filters provided by high voltage bushings shield UHF PD measurements against external disturbances [7]. Therefore, it is less susceptible to external interferences compared to the electrical method. This is advantageous for measurements in noisy environments for on-site / online measurements and for monitoring. CIGRÉ Working Group WG A2-27 recommends in brochure 343 to provide DN50 valves to all transformers for the later fitting of UHF probes. Alternatively, dielectric windows can be used for UHF sensors [8]. Both UHF sensors types are presented in the next chapter. Then a recommendation for the placement of window type UHF sensors at new power transformers is given. For the UHF method, a calibration procedure is now available [9, 10]. The calibration process is required to ensure both reproducibility and comparability of UHF measurements: only a calibrated UHF measurement procedure can be introduced supplementary to IEC 60270 in the acceptance tests of power transformers.

2. UHF sensors

A UHF sensor consists of a broadband antenna optimised for the UHF frequency range radiated by PD, and of its mechanical adaption for the installation on power transformers. Mainly two different mechanical adaptions for internal PD measurement are used for practical applications.

2.1 UHF drain valve sensor

A UHF drain valve sensor is designed for transformers, which are equipped with standard DN50 or DN80 gate valves, shown in Fig. 2a. A conventional gate valve with suited straight duct is shown in Fig. 2b. Ball and guillotine valves can also be used for sensor installation. Fig. 2c demonstrates a counterexample that is not suitable. It illustrates a globe valve without a straight opening. Other non-suited valve types without a straight opening (diaphragm and butterfly valves) are also popular in some regions. It is recommended to use only straight opening valves on new transformers to provide sensor compatibility.

Sensor application is possible even on transformers in service, which is advantageous, especially for diagnostic measurements on site. Nevertheless, permanent installation as part of an online PD monitoring system is possible as well. First, the UHF sensor is mounted on the valve. Secondly, the valve is opened slowly and deaerated by a small ventilation valve on the sensor's mounting plate. Afterwards, the oil valve can be opened completely, and the sensor is inserted into the transformer tank. The head of the UHF sensor (the antenna) has to only reach into the transformer in order to provide sufficient sensitivity. Usually, insertion depth of approx. 50 mm is a reasonable value [12]. If the UHF antenna remains inside the pipe of the gate valve, the sensor only provides low sensitivity due to electromagnetic shielding [3]. Besides sensitivity considerations, a minimum distance between the UHF sensor and parts on a high potential must be preserved to ensure safe operation.

2.2 UHF plate sensor

UHF plate sensors, as shown in Fig. 3a, can be mounted directly onto the tank wall, which is suitable for newly-built transformers or for transformers in repair. A dielectric window is integrated into the tank wall. It consists of a stainless-steel welding ring and a

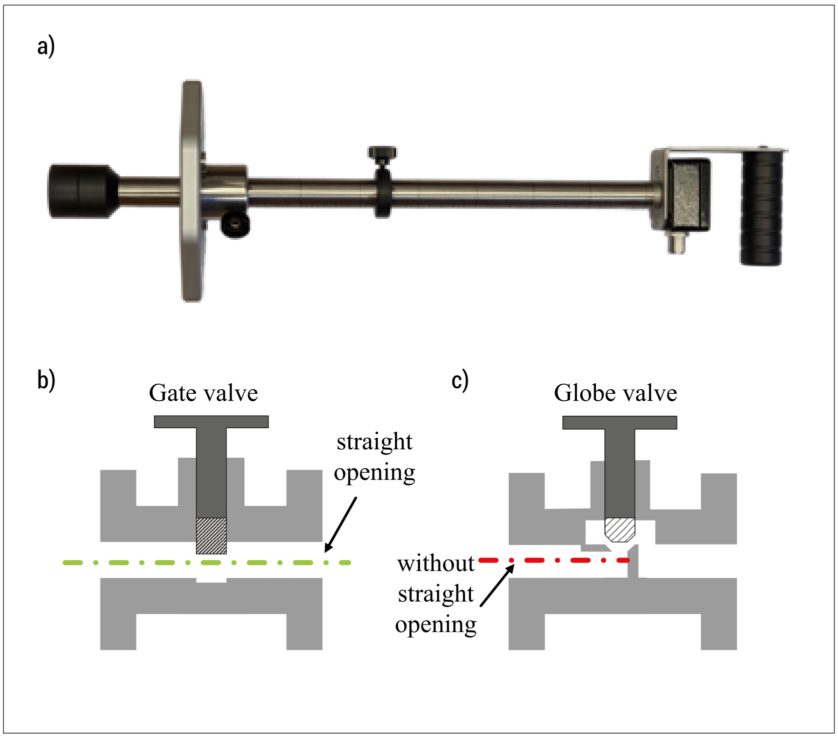


Figure 2. a) UHF drain valve sensor for DN50 / DN80 gate valves [11]; b) Gate valve example for oil valves suited for UHF sensor installation [12]; c) Globe valve example for oil valves not suited for UHF sensor installation [12]

> **There are two main types of UHF PD sensors: drain valve and plate sensor; plate sensors can be replaced without oil handling, which is not the case for the drain valve sensor**

high-performance high-temperature and oil-resistant plastic which serves as the oil barrier for the antenna. The plastic allows UHF signals to pass through with low damping. The plate sensor itself is mounted into the dielectric window. Its UHF antenna reaches into the transformer tank through the window. In contrast to the drain valve sensor, plate sensors are suitable for the replacement without oil handling. CIGRÉ Working Group WG D1-37 recommends a design for the welding ring and dielectric window (shown in Fig. 3b in the brochure TB 662 [13].

Fig. 3b shows a dielectric window and a welding ring suited for transformer tank wall installation. Plate sensors can be welded into the transformer tank at any suited position. Even if no sensors are installed initially, cheap dielectric windows with blank covers can be welded onto the tank wall during production, which allows an easy retrofit of UHF PD monitoring during service. Fig. 3c shows a test installation of three UHF plate sensor prototypes on a power transformer.

3. Calibration of UHF PD measurements

The comparability of electrical PD measurement systems is associated with their standardised calibration procedure. This enabled the introduction of acceptance levels using the apparent charge according to IEC 60270 in the transformer routine tests using the apparent charge level, even though the actual PD charge remains unknown and the significance is limited.

Both the measurable electrical and UHF PD levels are influenced by:

- Type and magnitude of the PD source
- Position of the PD and the related signal attenuation of the individual coupling path inside the transformer
- Sensor sensitivity (the UHF sensor, or the coupling capacitor and the quadrupole, respectively)
- Attenuation of measurement cables and the sensitivity of the particular measurement device.

For both PD measurement methods, the coupling path inside the transformer cannot be calibrated, which is why the actual PD source-level remains unknown in both cases. The goal of calibration is to ensure comparability between different measurement devices, which can be achieved by eliminating the influences of sensors and recording device [9, 14].

The standardisation of UHF PD measurement can also be achieved by using calibration. In contrast to the electrical PD calibration, the UHF calibration process consists of two steps because the specific antenna characteristics of the UHF sensor must be included separately into the entire calibration path. These characteristics must be obtained by the UHF sensor manufacturer as a pre-condition and then be included into the system calibration [10].

Therefore, UHF calibration is a two-step process. The first step results in the calibration factor K_M and eliminates the influence of the signal recorder and additional accessories, such as cable damping. This is achieved by the use of a defined impulse, which is injected into the UHF measurement system (no UHF sensor used). Hence, all deviations in the measurement can be corrected. The second step results with the calibration factor K_S. It takes into account an individual sensor's characteristics, namely its antenna factor (AF) into the calibration. The AF represents the ability of a sensor to convert the electric field strength into a voltage signal. It can be measured, for example, by using a defined and reproducible setup, such as a GTEM cell [15, 16]. The product of both factors with the measured voltage of the PD pulse U_{PD} results yields the calibrated field strength, which allows the comparability between different measurements. [10]

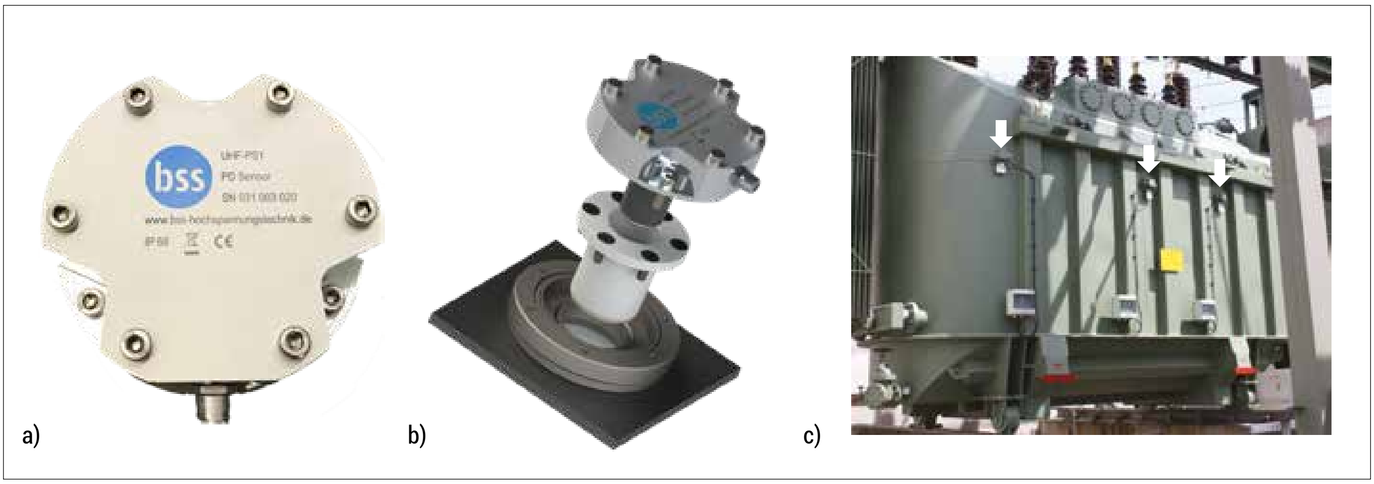


Figure 3. a) UHF plate sensor for the direct installation on the transformer tank wall [11]; b) 3D drawing of a welding ring (left), dielectric window (middle), and a UHF plate sensor (right) [11], c) Test installation of UHF plate sensors on a power transformer

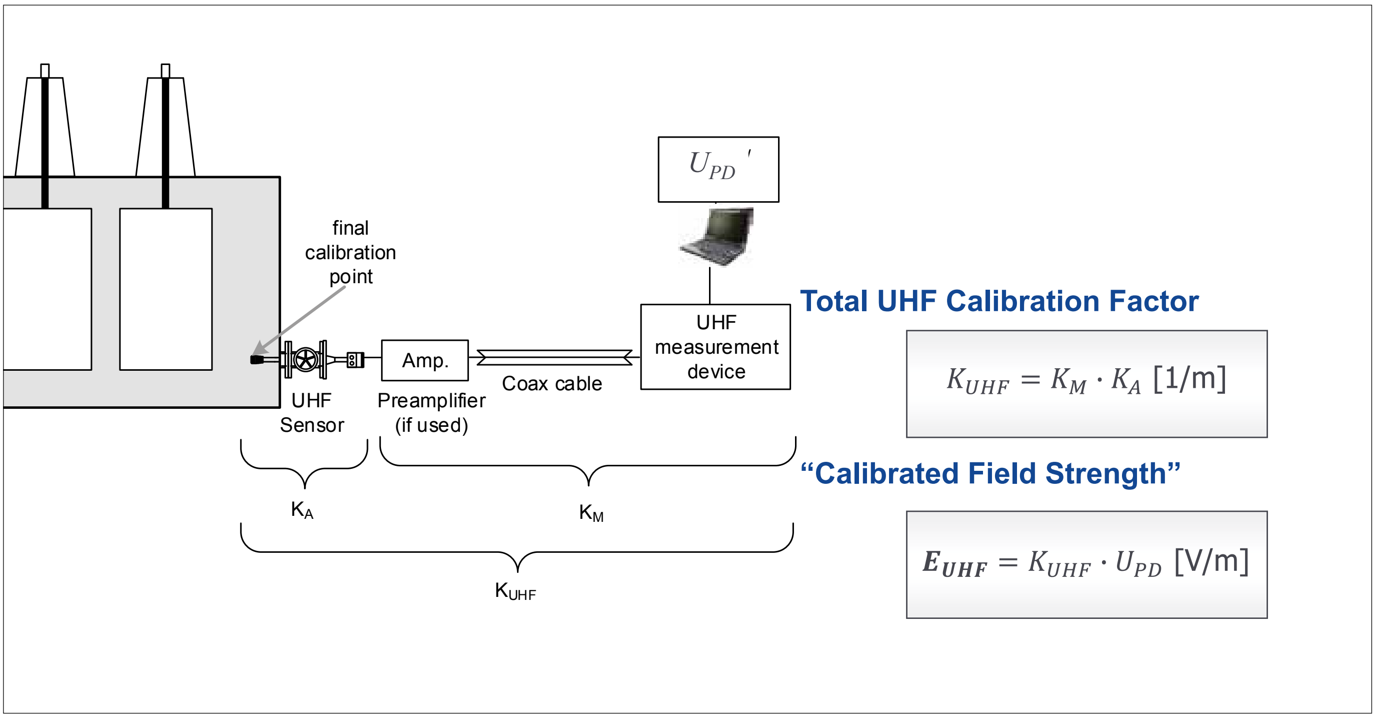


Figure 4. Determination of the calibrated field strength

The standardisation of UHF PD measurement can also be achieved by using calibration, which consists of two steps

4. Sensor placement recommendation for UHF PD monitoring

4.1 For partial discharge detection

To be used as a tool for acceptance test, it is necessary that the sensitivity of a PD measuring technique is sufficient to detect all PDs within a power transformer. Based on experimental results obtained from a 300 MVA, 420 kV transformer, a single UHF sensor is unable to provide sensitive coverage of the entire tank without the signal becoming noisy [17-19]. Therefore, at least two sensors are required to provide complete coverage of the tank. In addition, two sensors are necessary for the performance check procedure. Based on simulations carried out on a validated model of a power transformer [20], results show that when a PD source is situated inside the windings, the electromagnetic waves cannot propagate through the outer layer windings. Therefore, after hitting the inner surface of the outer winding, the waves are reflected radially and axially. The axially reflected waves emerge from the top and bottom of the windings and eventually propagate through the oil space in the tank. A similar phenomenon happens with the radially reflected waves after reaching the opposite side of the windings. The propagation characteristics of the waves, which can be observed in Fig. 5, have implications on the sensor positioning in that the sensors should be ideally placed above and below the highest and lowest points of the windings, respectively. The different colours show the electromagnetic field emitted by a PD in the centre of the main insulation gap between HV and LV winding 12 ns after the PD inception. Simulation results show that above the top height of the winding, detection of EM waves is indeed possible. Thus, the dotted lines in Fig. 5 represent the installation height thresholds of UHF PD sensors.

Experimental results show that installing one sensor on each lengthwise wall of the transformer tank provides complete coverage of the tank. The sensors should be ideally placed at the maximum possible spatial distance from one another and in an area with low electric field stress, i.e., away from the windings and HV lead terminals. Experiments performed on a transformer show that UHF sensors installed on the walls along the length of the transformer tank perform better when the propagation of the electromagnetic waves from the source to the sensor is direct, i.e., with minimal obstructions. If the PD occurs near the lead exits, then the propagation path can be assumed to be direct. However, PD occurring inside the windings will invariably have an indirect propagation path to such sensors. Therefore, sensor positioning should be done based on the signal attenuation with respect to both the signal propagation distance and the propagation path. Evaluation of the sensor performance shows that the sensors with the lowest signal attenuation are located near the outer return limbs of the yoke. Therefore, it can be stated that the receiving sensors located at these positions have a relatively better performance compared to the rest. Another beneficial aspect of placing a sensor close to the outer return limb is the low value of the encountered electric field stress since the sensor is not in close proximity to the windings. Hence, it is preferable to position the sensors near the outer limbs of the core in a diagonal formation on

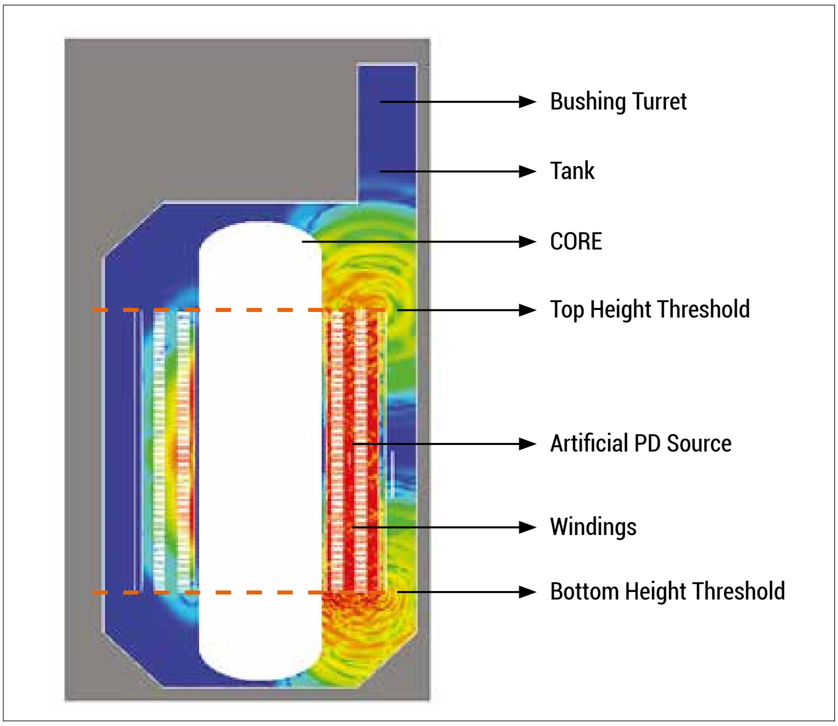


Figure 5. Electromagnetic wave propagation in the tank after 12 ns (side view)

Proper sensor placement at the tank is essential for high-sensitivity; at least two sensors should be installed to ensure complete coverage of the tank and detection of the UHF PD electromagnetic waves

the opposite sides of the tank wall, as shown in Fig. 6a. The general regions where sensors can be installed are denoted by the blue circles, with a diameter of approximately 100 cm. These positions also satisfy the requirements of the height thresholds, and two sensors placed at these positions should be adequate for the factory acceptance test.

4.2 For partial discharge localisation

The possibility of localisation of a PD sources is a benefit of the UHF method. Four or more sensors are required to triangulate the PD sources. The following requirements should be met for best sensitivity: the sensors should not be placed close to each other and on the same tank wall, and the sensors should not form a geometrical plane. These factors will result in insufficient deviations between the time difference of arrival (TDOA) of the signal at the sensors when the location of the PD source is changed, thus leading to lower sensitivity for localisation.

Based on the aforementioned observations from the measurement data, the optimal configuration would be four sensors in a cross-diagonal arrangement, as shown in Fig. 6b. The cross-diagonal formation maximises the spatial distance not only between

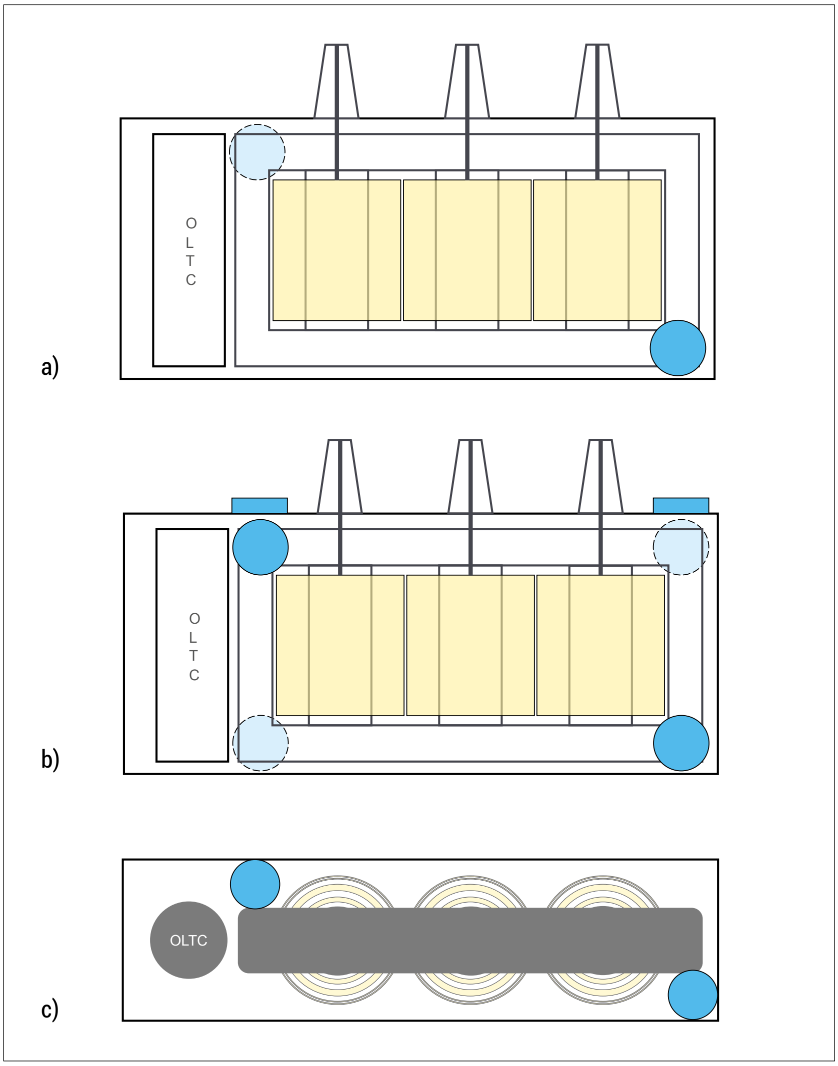


Figure 6. a) Sensor positioning for PD detection on opposite sides (view from the HV side)
b) Sensor positioning for PD localisation (view from the HV side)
c) Sensor positioning on the cover plate of the tank

In the case study, the PD trend analysis is used as an indicator to determine if the insulation defects are getting worse on 50-year-old 110 / 10 kV, 120 MVA step-up generator transformer

the sensors on the same side but also between those on the opposite sides. Additionally, the formation of a geometrical plane, which can lead to significant errors in localisation in certain scenarios, e.g., when a PD source is located along the normal at the geometrical centre of the plane, is prevented. Both factors should aid in localisation based on TDOA. Reliability can be improved by adding additional sensors. It should be noted that depending on the design of the tank and the presence of flux shunts, it may not always be possible to install the sensors at the proposed locations.

Based on the phenomenon shown in Fig. 5, it can be observed that installing sensors on top of the transformer tank will have benefits with respect to signal attenuation and propagation time compared to the positions at the tank wall. Additionally, there is the added convenience of the installation as there are fewer obstructions between the sensors and the active parts of the transformer. The results obtained from the simulations confirm that the sensors on top of the tank can measure the signals with the aforementioned advantages. The proposed alternative positioning of such sensors is shown in Fig. 6b, and Fig. 6c, where two sensors should be placed in a diagonal formation on top of the tank instead of on the sidewall.

For safety reasons, dielectric windows need to be placed in regions with low electric field strength. In the areas with high electrical field strength, the air inside the pocket of the dielectric window could lead to PD. It is advisable to follow these estimated guidelines regarding the minimum installation distances with respect to the HV winding. For windings rated at 420 kV, 230 kV, and 130 kV, the minimum distances of 1.5 m, 1 m, and 0.8 m, respectively, are recommended.

5. UHF PD monitoring case study: 120 MVA generator step-up-unit

This case study presents PD monitoring data of an approx. 50-year-old 110 / 10 kV, 120 MVA unit generator transformer, which has by now been monitored for more than six years. Prior to this, the transformer was out of service for eight years. A condition assessment before bringing the unit back into service indicated PD: conventional PD measurements, according to IEC 60270 [2], indicating that the transformer had several active PD sources at nominal voltage U_N.

Due to the lack of standard rules and threshold values to assess old transformers, it was decided that the unit can only be put back into service with continuous PD monitoring. For permanent observation of PD data, an online UHF PD monitoring system with a single UHF drain valve sensor was installed. Furthermore, voltages, load currents, top-oil / ambient temperatures, mechanical vibrations, and dissolved gases (using a GE Hydran sensor), were recorded. The PD trend is used as an indicator to determine if the insulation defects are worsening. PRPD monitoring data confirms the presence of more than one PD source. The PDs are not present permanently despite constant voltage conditions. Because the measured PDs show no clear trends, alarm thresholds are set slightly over the "normal" PD behaviour. Alarm parameters are given by the maximum signal amplitude of UHF PD (in mV) and by the counted PD events per minute. Fig. 7a shows a UHF PRPD pattern and Fig. 7b the same PRPD data time-resolved, whereas the colour gradient in Fig. 7a represents the number of recorded PD per minute and in Fig. 7b the UHF amplitude in mV. The UHF PRPD pattern in Fig. 7a shows the PRPD data from Fig. 7b from $t_1 = 240$ min to $t_2 = 420$ min. High UHF signals occur in this timeframe which triggered the amplitude alarm of the system. During this time frame, the amplitude and number of PDs stayed constant and did not get worse, so it was decided to keep the transformer in service. After 3 h of high amplitudes, the PD event vanished, and PD activity was normalised. The measured combined dissolved fault gases represented by the Hydran value started to increase approx. 4 h after the PD event was over. Fig. 7c shows the trend view of the PD amplitude correlated to the Hydran value.

The alarm threshold for the fault gas value was exceeded approx. 7 h after the PD event started. This delay is caused by the gas solubility and dispersion in the transformer. The event illustrates the advantage of direct PD monitoring. The UHF PD monitoring system provides an instant alarm in case of PD events, and PD can be observed using PRPDs and trend views. In contrast, the DGA monitoring alarm occurs with several hours delay (in this case) and no detailed information about the causing PD itself.

Conclusion

In this contribution, the placement of UHF PD sensors in power transformers was discussed, and a case study of continuous UHF PD monitoring data obtained from a 120 MVA power transformer was presented. Out of the two types of UHF PD sensors introduced, the drain valve sensors can be installed in transformers equipped with standard DN50 or DN80 gate valves, whereas UHF plate sensors are installed in dielectric windows provided on the transformer tank wall. The former type is limited by the number and the location of available gate valves, while the dielectric windows can be placed on the transformer tank wherever desirable on new transformers.

Comparability of UHF PD measurements can be achieved using calibration. The UHF calibration process consists of two steps because the specific antenna characteristics of the UHF sensor must be included separately into the entire calibration path.

The sensor placement strategies for window type UHF sensors were based

The UHF PD monitoring system provides an instant alarm in case of PD events, and PD can be observed using PRPDs and trend views

on the experimental data and electromagnetic simulations. Both the sensor sensitivity and electric field strength were taken into account while making the recommendations. The benefits and demerits of placing sensors on various sides of the transformer tank were also discussed. With respect to factory acceptance tests, two sensors are deemed to be sufficient. However, for PD source localisation, four or six sensors are recommended.

The power transformer used in the case study had multiple active PD sources. However, the PD activities did not show a clear trend, and they normalised after a certain time. An attempt was made in correlating the PD activity to the amount of gas dissolved in oil. The alarm of the DGA monitoring system sounded approximately 7 hours after the end of the PD event and provided no information about the cause, thus highlighting the importance of direct PD monitoring using UHF sensors.

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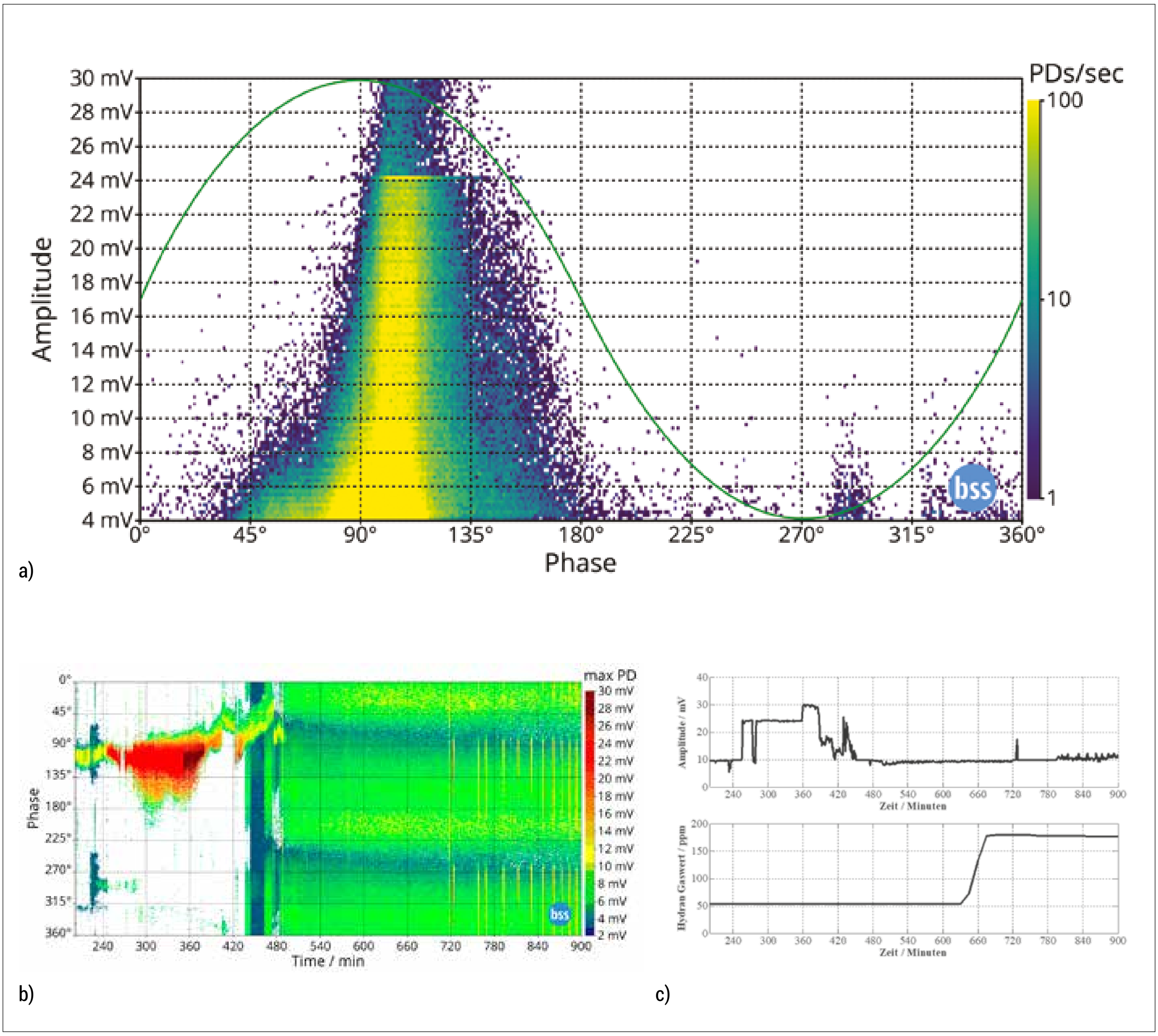

Figure 7. a) UHF PRPD (section 240 min – 420 min in b)), b) time-resolved PRPD (2-dimensional simplification, no #PDs shown) c) UHF PD value (in mV) correlated with Hydran value (in ppm)

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