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Partial Discharge Monitoring of Power Transformers by Calibrated UHF Measurements

Martin Siegel, Christoph Kattmann, Chandra Prakash Beura, Michael Beltle, Stefan Tenbohlen

Summary **— Partial discharge (PD) measurement is an established technique to detect local defects in the oil/paper insulation. They can be measured by electrical PD measurements according to IEC 60270 or by electromagnetic measurements in the ultra-high frequency range (UHF: 300 MHz – 3 GHz). The electromagnetic emissions of PD are recorded using an UHF sensor which is inserted into the transformer tank. The importance of PD measurements is reflected in the standard for charge-based electrical measurements (IEC 60270). Because of the standard, apparent charge, Q_{IEC}, became an essential factor for determining insulation quality in transformers. To be an accepted factor for both, quality testing in factory acceptance tests (FAT) or site acceptance tests (SAT) and continuous PD monitoring, the UHF technology must be as reliable and reproducible as the electrical method. To achieve this, a standardized calibration procedure is needed: It makes UHF measurement results from different systems comparable. Because this calibration procedure was lacking in the past, the UHF technology does not provide comparability between measurement systems and different sensors, yet. However, it shows advantages for on-site acceptance tests like SAT, continuous monitoring, and diagnostic purposes. E.g., regarding signal to noise ratios, the possibility for localization of PD sources and also for practical reasons like preparation times and accessibility on-site. This contribution presents a PD monitoring system which can be calibrated according to the calibration process described recently in Cigré TB 861 and two different types of UHF PD sensors for power transformers. One sensor type is for new transformers using dielectric windows and the other is for retrofitting transformers using their DN50/80 drain valves. A recommendation or strategy on where to place window-type UHF sensors at the tank of new power transformers is also provided in accordance with TB 861. Additionally, this contribution provides a description of the calibration process for UHF PD measurement systems consisting of two steps: 1) Calibration of the measurement instrument analogous to the calibration of the electrical PD measurement circuit using a defined reference signal. 2) Calibration of a UHF sensor using its characteristic antenna factor (AF). Furthermore, it shows three case studies from different power transformers equipped with UHF sensors and UHF PD monitoring systems.**

Keywords **— power transformers, partial discharge, PD, UHF, monitoring, sensors.**

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I. Introduction

The reliability of the electrical power grid depends on power transformers. Significant damage and related costs are incurred when a transformer fails. It is important to find any internal damage that is critical as soon as possible. To meet the rising demand for onsite and offsite measurements, various diagnostic techniques have been created [1].

Dissolved gas analysis (DGA) can detect partial discharges indirectly, and electrical PD measurements in accordance with IEC 60270 [2], or by electromagnetic measurements in the ultra-high frequency range (UHF: 300 MHz – 3 GHz)

[3] can detect PD directly. DGA provides a hint for the potential presence of Partial Discharge (PD) in transformers. The use of direct monitoring methods for transformers is increasing. By employing PD measurements, damages to the insulation of power transformers can be quickly identified and subsequently repaired, thereby reducing the risk of transformer failure [4]. Standardized electrical measurement in accordance with IEC 60270, which is required for acceptance at routine testing, highlights its importance. An indication of the quality of a transformer is the conducted apparent charge Q_{IEC}. In terms of monitoring and on-site diagnostics, the electromagnetic UHF method is becoming more significant [5]. The radiated electromagnetic emissions of PD are recorded using an UHF antenna which is installed into the transformer tank. The general differences of the propagation paths of both methods are shown in Figure 1.

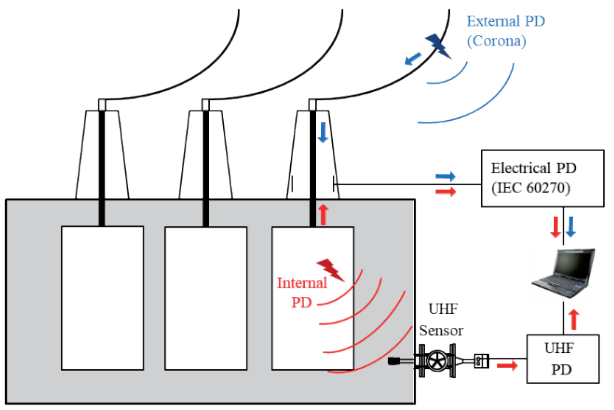

Fig. 1. Signal propagation of UHF and electrical PD measurement at a power transformer with internal PD (red) and external PD (blue) [6]

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Galvanic coupling allows electrical PD signals to travel through the winding before being decoupled by an external coupling capacitor or by the C_1 capacitance of the bushing for online monitoring. As electromagnetic waves, UHF signals travel through the transformer's oil volume. With the exception of non-graded mid- and low-voltage bushings, the transformer's tank and the low-pass filter of the high-voltage bushings typically protect the UHF PD measurements from outside interference [7]. As a result, when compared to the electrical method, UHF has a tendency to be less susceptible to outside interference. This is advantageous for measurements made in noisy environments, such as those made during continuous PD monitoring and on-site/online PD measurements. As a consequence, Cigré Working Group A2-27 recommends in TB 343 that all transformers should be equipped with DN50 valves for subsequent installation of UHF probes. It also states, that alternatively, dielectric windows can be used for UHF sensors [8]. Both UHF sensor types are discussed in the next chapter. In the subsequent chapter, a recommendation for the placement of window-type UHF sensors at new power transformers is given. Since 2020, a calibration procedure has been introduced [9, 10] which was also incorporated into Cigré TB 861 in 2022 [11]. The method is adopted from established calibration procedures for EMC measurements of radiated emissions defined in CISPR 11 and CISPR 16 [12, 13]. The main target is to ensure reproducibility and comparability of UHF measurements. Both are mandatory for an UHF measurement procedure which can be eventual introduced supplementary to IEC 60270 in the acceptance tests of power transformers.

The primary drawback of the UHF method persists in the demand from many users for a displayed value in picocoulombs (pC) out of convention. Unfortunately, establishing a consistent conversion from radiated UHF measurements to galvanically coupled pC measurements is not universally feasible. In the future, experience must be gained using calibrated UHF measurements to be able to classify the resulting measured UHF PD values, as has been done with the calibrated pC values according to IEC 60270 in the past. One of the main advantages of UHF, the fact that the low-pass filter effect of the capacitive graded high-voltage bushings typically protects UHF PD measurements from outside interference such as corona signals, can also be interpreted as a disadvantage for the detection of PD directly inside the bushings.

II. UHF PD Monitoring System

A comprehensive UHF PD monitoring system for power transformers mainly consist of suitable UHF sensors (described in the following chapter III) and a measurement system which is capable of continuous UHF PD measurement. Such a system should encompass the following features and functionalities:

In many cases, having just a single UHF sensor is inadequate for large power transformers because of their size. To address this, the measurement system should be equipped with multiple analog input channels, enabling simultaneous and ongoing measurement across all these channels. The analog inputs should be capable of the UHF frequency range from approx. 100 – 300 MHz to 2 – 3 GHz with high sensitivity, e.g. -75 dBm, and high dynamic range, e.g. 70 dB. Such a UHF PD measurement system should incorporate data storage and processing capabilities to analyze and interpret PD measurements effectively, e.g., PRPD and trend visualizations. A long-term storage of historical PD data is essential for trend analysis and diagnostics using monitoring data. Also, it should incorporate the option for calibration following the methodology described in Cigré TB 861 [11], as elaborated in chapter IV of this publication.

For the use as a stand-alone PD monitoring solution, the system should feature isolated relay outputs to trigger alerts and actions. A graphical user interface with data visualization tools for real-time and historical PD data analysis is essential for stand-alone monitoring systems, whereas for seamless integration into overlayed monitoring or SCADA systems a UHF PD monitoring measurement system should support industry-standard communication protocols such as ModbusTCP and IEC 61850.

Figure 2a) shows a 2-channel version of a PD monitoring system which can be equipped modularly with up to six analog input channels for electromagnetic (UHF), electrical charge-based (IEC 60270) and acoustic PD measurement. Figure 2b) shows its web interface with a rich visualization of live and historical PD data. It is also compatible not only with power transformers UHF sensors, but also to already installed UHF couplers in GIS for example.

a)

b)

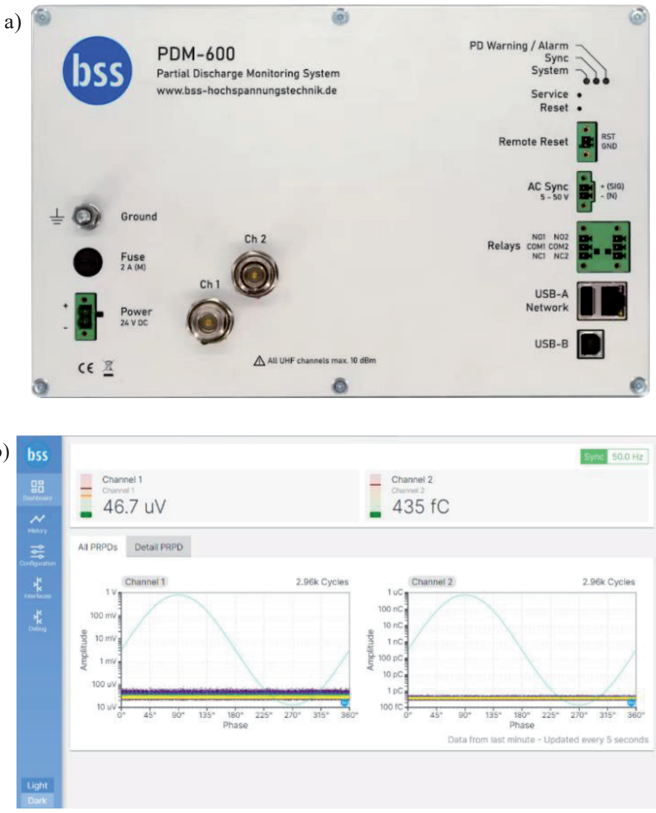

Fig. 2. a) PD monitoring system with 2 UHF channels [14]; b) web-based GUI showing live PD values and PRPDs

III. Types of Uhf PD Sensors

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

A. Drain Valve UHF Sensor

A UHF drain valve sensor (Figure 3a) is designed for transformers, which are equipped with standard DN50 or DN80 gate valves, shown in Figure 3b. Ball and guillotine valves can also be used for sensor installation. To ensure sensor compatibility, it is advised to use straight opening valves on new transformers. The sensors can be installed temporarily on transformers that are in use or being serviced, which is advantageous for on-site diagnostic tests. Permanent installations as a part of an online PD monitoring system are, of course, also possible. To ensure adequate sensitivity, the UHF sensor's head must extend into the transformer's oil space. For most sensor types, an immersion depth of about 50 mm is

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usually a reasonable value [15]. If the UHF antenna remains in the pipe of the gate valve, the sensor has only a low sensitivity due to the electromagnetic shielding [3].

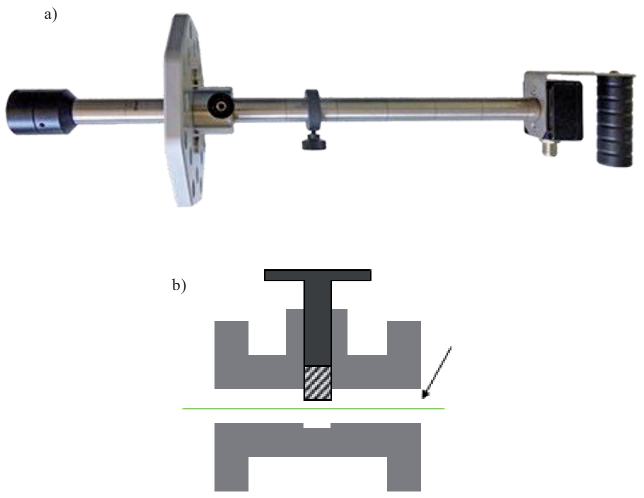

Figure 3 a) UHF drain valve sensor for DN50 / DN80 gate valves [14]; b) Gate valve example for oil valves suited for UHF sensor installation with straight opening [15]

B. Window-Type UHF PD Sensor

For newly constructed transformers or transformers undergoing repairs, window-type UHF sensors, as shown in Figure 4, can be welded directly onto the tank wall. The sensor incorporates a dielectric window. It consists of a stainless-steel welding ring and a high-performance high-temperature and oil-resistant plastic which serves as the oil barrier. Low damping is required for UHF signals to pass through the plastic. The actual sensor is fixed inside the dielectric window (on the air side). Its UHF antenna reaches into the transformer tank inside the dielectric window. Window-type UHF sensors, as opposed to drain valve UHF sensors, can be replaced without handling oil. Cigré Working Group D1-37 recommends a standard design for the welding ring and dielectric window (shown in Figure 4 a) in brochure TB 662 [16] to provide interoperability between sensor manufacturers. Dielectric windows can be located at the transformer tank wall at any suitable location and compatible sensors can then be installed later if needed (UHF PD sensor ready setup).

IV. Calibration of UHF PD Measurements

A standardized calibration procedure in accordance with IEC 60270 ensures the comparability of electrical PD measurement systems and allowed the introduction of acceptance values using the apparent charge Q_{IEC} in the transformer routine tests, although the actual PD charge at the fault location remains unknown.

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 specific coupling path within the transformer tank
- Sensor sensitivity (the UHF sensor, or the coupling capacitor and the quadrupole, respectively)
- Attenuation of measurement cables (more relevant at higher frequencies) and the sensitivity of the particular measurement device.

The coupling path within the transformer cannot be calibrated for either of the PD measurement techniques, leaving neither method's actual PD source level unknown. By removing the influences of sensors and recording devices, calibration can be used to ensure comparability between various measurement devices [11, 17].

Similar to the IEC 60270, a calibration procedure can be used to standardize UHF PD measurement. The UHF calibration procedure, in contrast to electrical PD calibration, entails two steps: calibration of the sensor (by its specific frequency dependent conversion from input electric field to output voltage) and calibration of the combined setup of the entire signal path after the antenna (measurement cable, recording system, amplifier and filters if used).

Therefore, UHF calibration is a two-step process shown in Figure 5. The first step results in the calibration factor K_M and eliminates the influence of the signal recorder and additional accessories, such as additional amplifiers and cable attenuation. This is achieved by using a defined pulse fed into the UHF measurement system at its connection point to the antenna (no UHF sensor is used). This allows any deviations in the measurement to be correc-

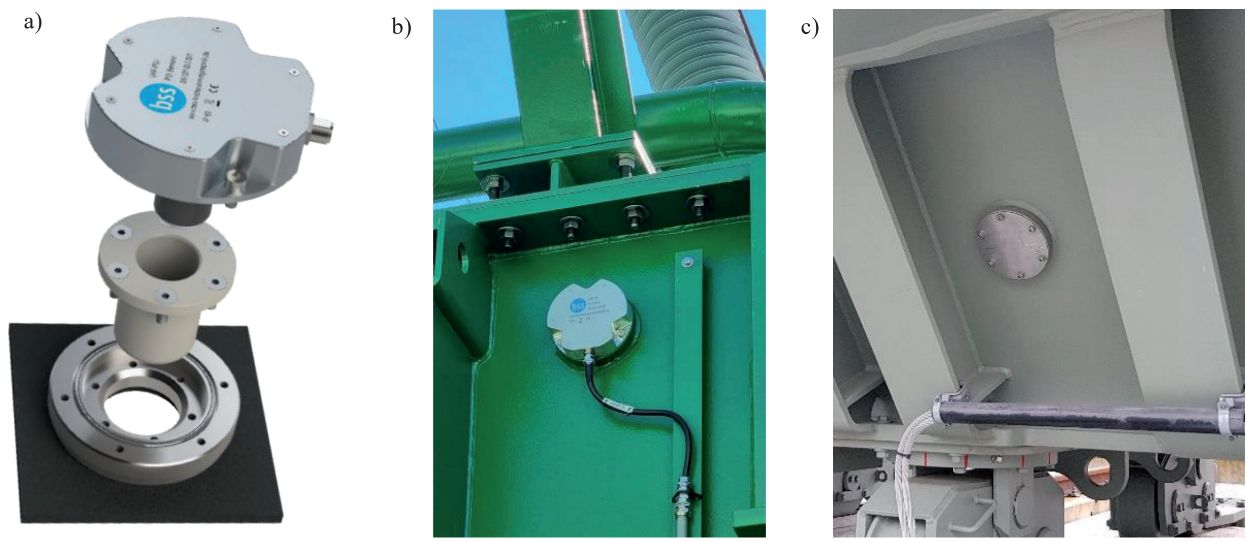

Fig. 4. a) 3D drawing of a welding ring (bottom), dielectric window (middle), and a window-type UHF sensor (top) [14]; b) Installed window-type UHF sensors on a power transformer; c) Dielectric window with blind cover plate (UHF PD sensor ready setup)

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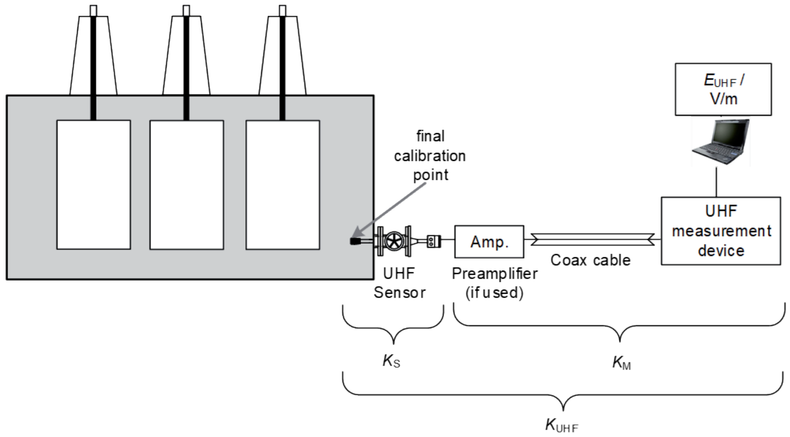

$$K_{\mathrm{UHF}} = K_{\mathrm{M}} \cdot K_{\mathrm{S}} \quad [1/\mathrm{m}]$$

$$E_{\mathrm{UHF}} = K_{\mathrm{UHF}} \cdot U_{\mathrm{i}} \quad [\mathrm{V/m}]$$

U_i: Indicated amplitude by the UHF instrument
K_M: Measurement device calibration factor
K_S: Sensor calibration factor
K_{UHF}: Resulting calibration factor
E_{UHF}: Measured UHF electrical field strength (after calibration is applied)

Fig. 5. Determination of the calibrated UHF field strength [10]

ted. The second step is performed with the K_S calibration factor. It considers the characteristics of a single sensor, namely its antenna factor (AF), during 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, with a defined and traceable setup, such as a GTEM cell [18, 19]. These characteristics must be determined by the UHF sensor manufacturer as a precondition so it can then be calculated into the system calibration [9]. The product of both factors with the measured voltage U_i results in the calibrated measured UHF field strength E_{UHF}. which allows comparability between different measurements [9].

V. Sensor Placement Recommendation for UHF PD Monitoring

To be used as a tool for acceptance test, it is necessary that the sensitivity of a PD measuring technique is sufficient to detect ideally 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 coverage of the entire tank without the signal becoming noisy [20]. Therefore, at least two sensors are required to provide complete coverage of most tanks. In addition, two sensors are necessary for the performance check procedure (where an impulse is injected into the first sensor and measured by the second to check if both sensors are installed correctly meaning electromagnetically not shielded from the inside of the transformer). Therefore, with respect to factory acceptance tests, two sensors are deemed to be sufficient. However, for UHF based PD source localization, four (shown in Figure 6b) or six sensors are recommended [11].

Results from simulations conducted on a validated power transformer model [21] indicate that if a PD source is located within the windings, electromagnetic waves cannot propagate through the outer layer of windings. Instead, upon encountering the inner surface of the outer winding, the waves are reflected both radially (inward) and axially (along the cooling channels). The axially reflected waves emerge from the top and bottom of the windings and eventually propagate through the oil space in the tank. The simulated propagation characteristics of the waves, which can be observed in Figure 6a, have implications on the sensor positioning: The sensors should be ideally placed above and below the highest and lowest points of the windings, respectively. The different colors show the electromagnetic field (its electric field strength) emitted by a PD in the center of the main insulation gap between HV and LV winding at 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 red lines representing the windings bottom / top in Figure 6a represent the installation height thresholds of UHF PD sensors. Experimental results demonstrate that complete tank coverage is achieved by installing one sensor on each lengthwise wall of the transformer tank. [20]. Ideally, the sensors should be positioned at the maximum achievable spatial separation from each other to optimize coverage. Additionally, they should be located in areas with low electric field stress. Experiments conducted on a transformer indicate that UHF sensors

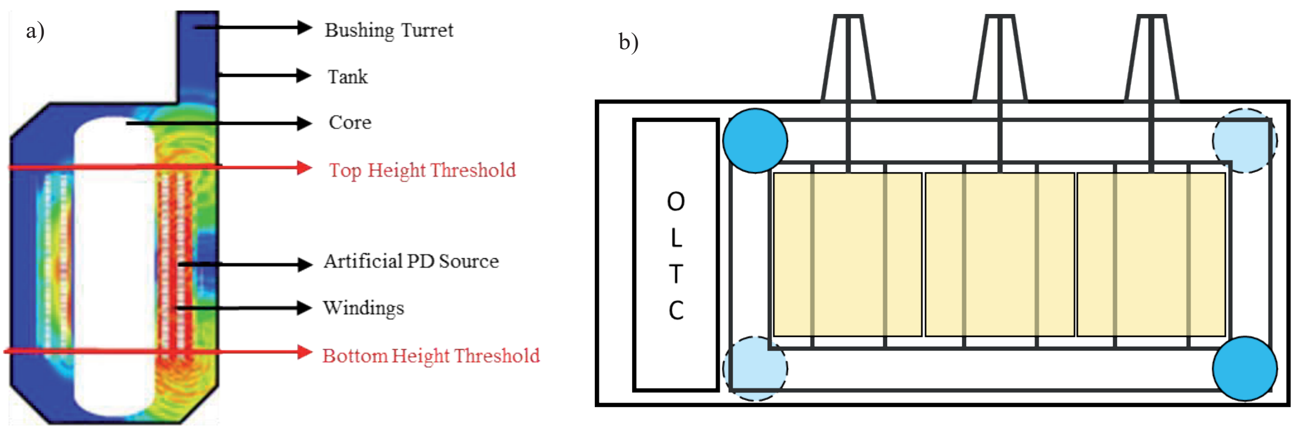

Fig. 6. a) Electromagnetic wave propagation in the tank after 12 ns (sideview) [21]; b) Example for window-type UHF sensor positioning with four sensors [20] complying to the recommendations above.

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installed on the lengthwise walls of the transformer tank exhibit improved performance when the propagation of electromagnetic waves from the source to the sensor is direct, meaning that minimal obstructions are present. [20]. If the PD occurs near the lead exits, the propagation path can be assumed to be direct. PD inside the windings will inevitably follow an indirect propagation path to reach the sensors (see Figure 6a). Consequently, sensor placement should be determined by signal attenuation concerning both the signal's propagation distance and its propagation path.

An assessment of sensor performance reveals that positions with the least signal attenuation are found near the outer return limbs of the yoke, as indicated by the markings in Figure 6b [22]. Positioned at these locations, sensors exhibit relatively superior performance in comparison to others. Another advantageous aspect of siting a sensor in proximity to the outer return limb is the diminished electric field stress experienced, as the sensor remains further away from the windings, see next paragraph. Hence, it is advisable to place the sensors near the outer limbs of the core forming a diagonal pattern on opposing sides of the tank wall.

For safety reasons, dielectric windows need to be placed in regions with low electric field strength with sufficient distance from the windings and HV lead terminals. Otherwise, for areas with high electrical field strength the air inside the pocket of the dielectric window could lead to PD. It is advisable to follow 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 [11].

VI. Use Cases

In this chapter, three UHF PD monitoring use cases are presented, each possessing distinct characteristics. One case describes the installation on new power transformers, one describes a retrofit on an old power transformer with known PD issues and one describes the use of UHF PD monitoring after a power transformer fault and repair. The cases occurred prior to the release of CIGRÉ TB 861; as a result, calibration was not conducted on the systems in use. Therefore, the shown PRPD plots show the raw input data of the measurement system (in millivolts).

A. Online Monitoring of Four Identical New Power Transformers

A UHF PD monitoring system was installed at two substations, each equipped with 130 kV power transformers. A total of 12 window-type UHF sensors was installed during the manufacturing of the transformers. Each transformer was connected to a 3-channel PDM-600 PD monitoring system during commissioning, see Figure 7.

In service, PD warnings were triggered on two systems shortly after energization of the transformers. The remote analysis of the PRPDs revealed a stable pattern (see Figure 8, raw input data shown). Other monitoring equipment did not measure any irregularities.

The patterns indicated air bubbles in oil. The source of these gases might be a weakness in the insulation system or an improper filling of the transformer (e.g. non-degassed oil, improper vacuum) and be prone to damages in the future. It was decided to continue normal operation and observe the PD level and patterns for any increase in activity or change in pattern shape. After a few days, the patterns disappeared on both transformers. Accordingly, it was probably not a defect that was outgassing, but trapped air during filling with oil. Since then, monitoring continued and there have been no more abnormalities in the PD data.

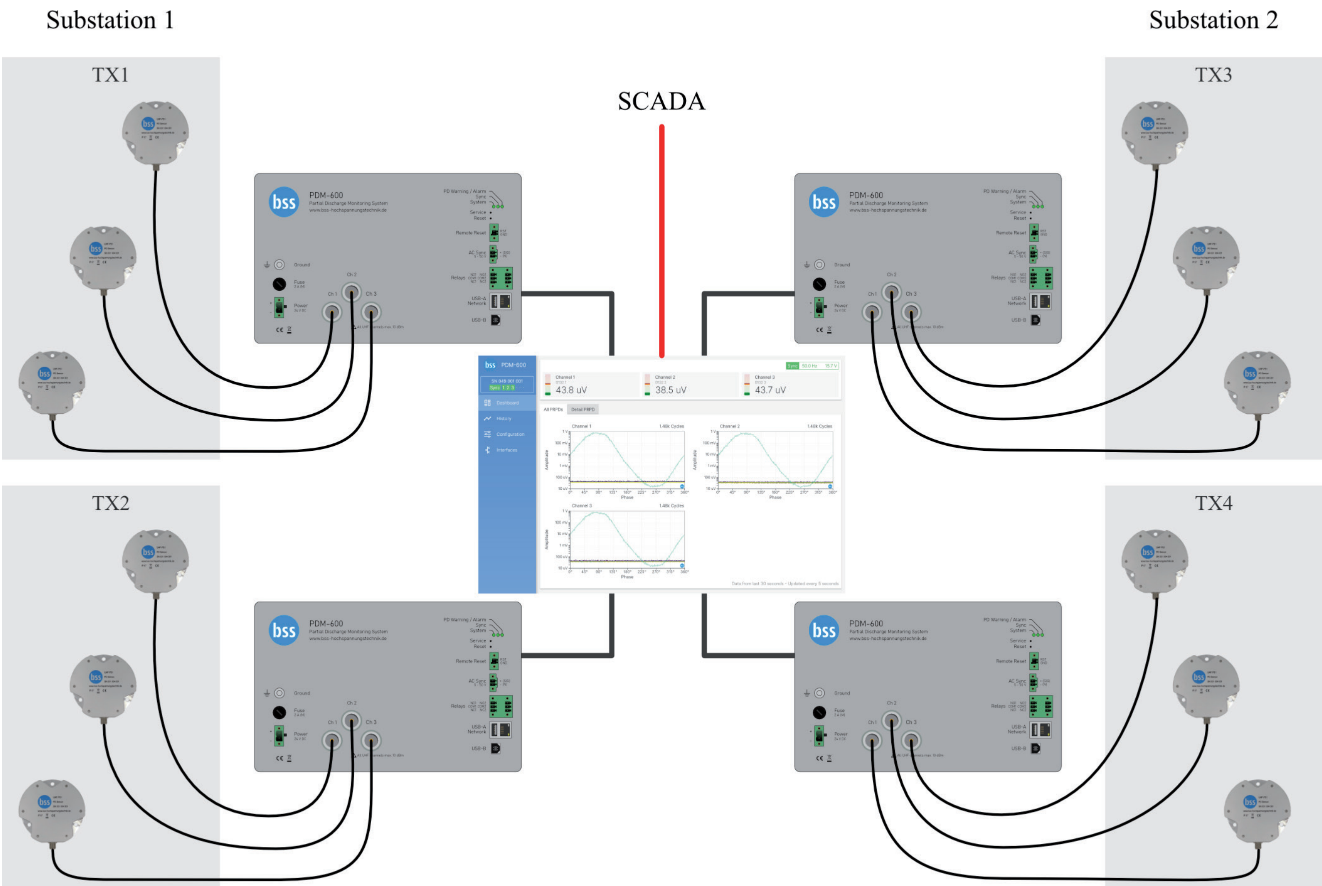

Fig. 7.: Topology of PD monitoring installation with four transformers in two substations

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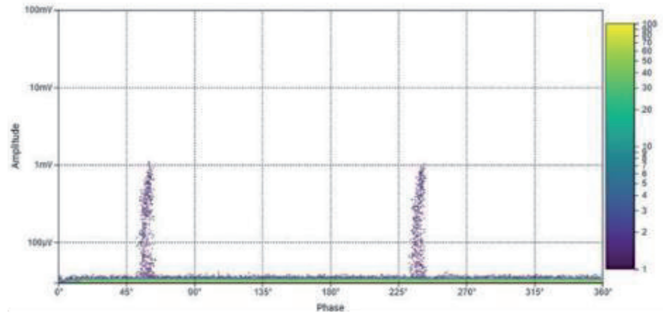


Fig. 8. PRPDs recorded at two of four transformers.

B. Online Monitoring of a 50-year-old 120 MVA, 110 / 10 kV Generator Transformer

This case study presents PD monitoring data of a 50-year-old 110 / 10 kV, 120 MVA generator transformer, which has been monitored for more than six years. Prior to this, the transformer was as a spare unit 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 with a maximum of 1000 pC.

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, a UHF PD monitoring system with a single UHF drain valve sensor was installed (only one gate valve was available). Furthermore, voltages, load currents, top-oil / ambient temperatures, mechanical vibrations, and dissolved gases were recorded. The PD trend was used as an indicator to determine if the insulation defects are worsening. PRPD monitoring data confirmed the presence of more than one PD source. The PDs were not permanently present despite operation of the transformer. Figure 9a shows a UHF PRPD pattern and Figure 9b the same PRPD data time- resolved, whereas the color gradient in Figure 9a represents the number of recorded PD per minute and in Figure 9b the UHF amplitude. The UHF PRPD pattern in Figure 9a shows the PRPD data from Figure 9b from a measurement time set t_1 = 240 min to t_2 = 420 min. High UHF signals occurred in this timeframe which triggered the PD 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, but under close surveillance. After 3 h of high amplitudes, the PD event vanished, and PD activity normalized. The measured combined dissolved fault gases started to increase approx. 4 h after the high amplitude PD event was already over.

Figure 10 shows the trend view of the PD amplitude correlated to the combined dissolved gas value.

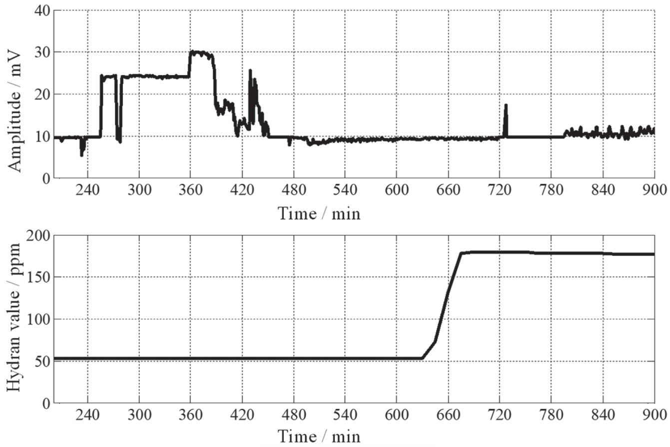


Fig. 10. UHF PD value (top plot) correlated with combined dissolved gas (Hydran) value in ppm (bottom plot)

The alarm threshold for the fault gas value was exceeded approx. 7 h after the high amplitude 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.

C. Online Monitoring of Repaired 40 MVA, 123 kV Substation Transformer

After internal flashover, the active part of a 15-year-old 123 kV substation transformer was cleaned from deposits and carbon particles. After repair, an induced voltage test with partial discharge measurement (IVPD) according to IEC 60076-3 was performed

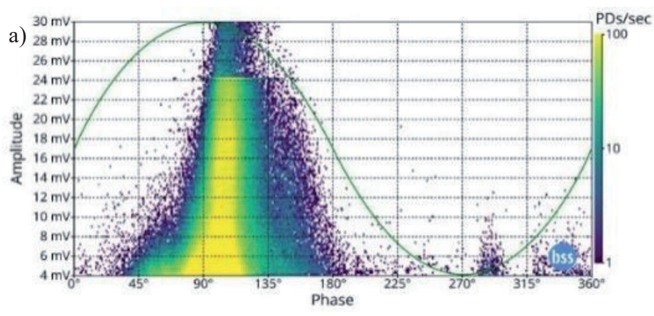
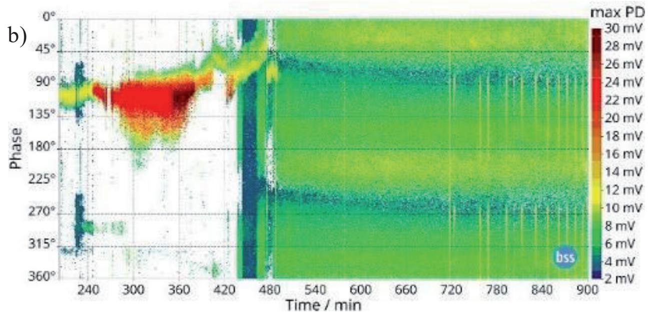


Fig 9. a) UHF PRPD (section 240 min – 420 min in b);



b) time-resolved PRPD (2-dimensional simplification, no #PDs shown)

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with 80% of the original test level. The test voltage was provided by an inverter. During service, the switching operation of the thyristors produced an interference level of more than 3 nC for the IEC 60270 charge-based PD measurement, which increased to approx. 7.8 nC with increased voltage. Figure 11 shows the charge-based PRPD with thyristor driven disturbances igniting six times within one period. The detection and evaluation of PD with the IEC 60270 based PD measurement system was therefore not possible.

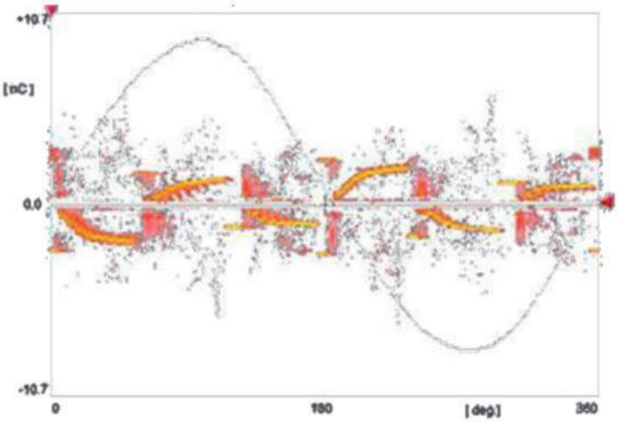

Fig 11. charge-based PRPD according to IEC 60270 with inverter-fed disturbances during factory induced voltage test.

Therefore, the induced voltage test was repeated by using the UHF PD measurement technique which was not affected by the inverter sources. UHF measurements showed significant internal PD (see Figure 12a and Figure 12b). Due to this critical test result, the transformer was equipped with an online PD monitoring system to assess the insulation condition on a permanent basis. Regular oil samplings with particle counting were also carried out.

For UHF PD monitoring, two UHF drain valve sensors were installed on two DN80 oil gate valves. Sensor 1 was mounted on the oil drain valve at the bottom of the tank, while sensor 2 was mounted on the oil valve on top of the tank. Both antennas were installed with an insertion depth of 50 mm to ensure adequate sensitivity.

The online PD monitoring system detected PD activity by both UHF sensors (see Figure 13). The amplitude of the top UHF sensor was higher, see Figure 13b.

Figure 14 illustrates a significant dependence of PD amplitude on oil temperature. This dependence is evident in both short-term and long-term trends. It may result from the temperature-dependent floating behavior of carbon particles that remained within the active part, despite cleaning efforts.

The sustained decline in PD activity over the long term was further validated by DGA samples, as depicted in Figure 15. Nonetheless, owing to the considerably reduced time resolution of DGA analyses when compared to UHF PD monitoring, operational factors such as oil temperature or loading cannot be observed. This use case illustrates how continuous UHF PD monitoring can ensure the secure operation of a network, even in the presence of a problematic transformer.

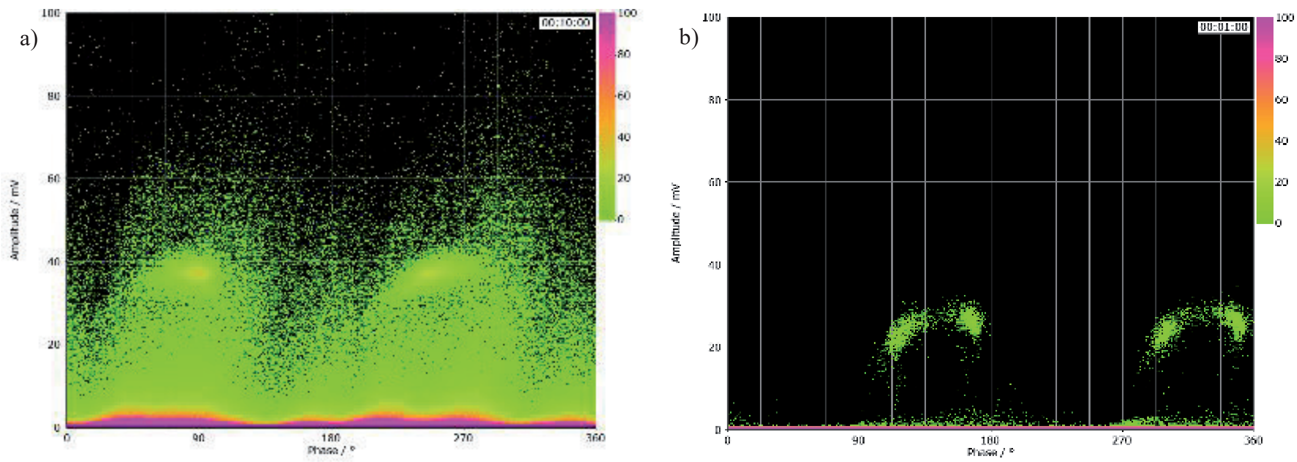

Fig 12. PRPD pattern during factory induced voltage test measured using a UHF drain valve sensor (top); a) at 145 kV; b) at 123 kV

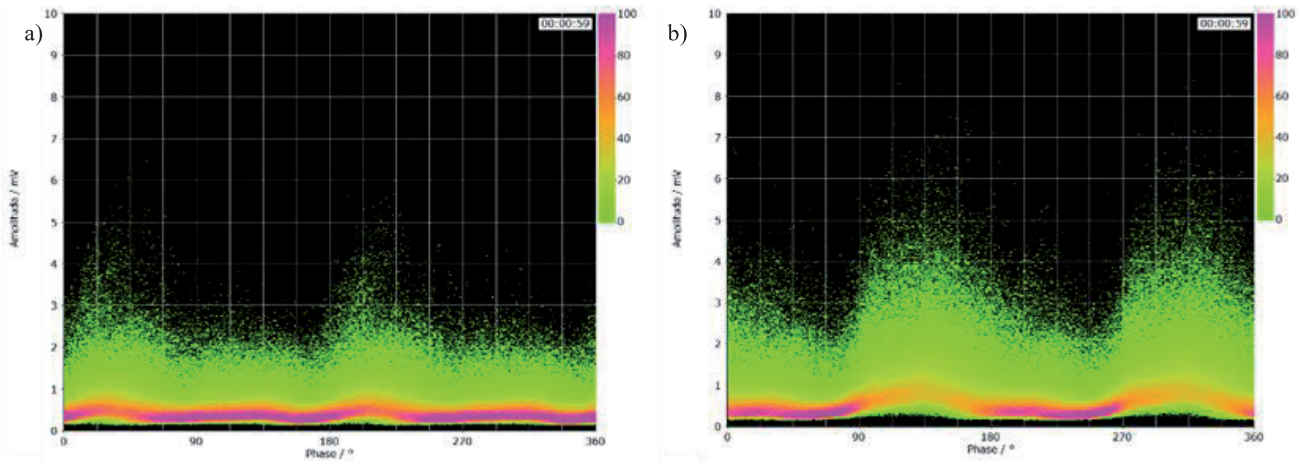

Fig 13. PRPD pattern during operation; a) bottom b) top

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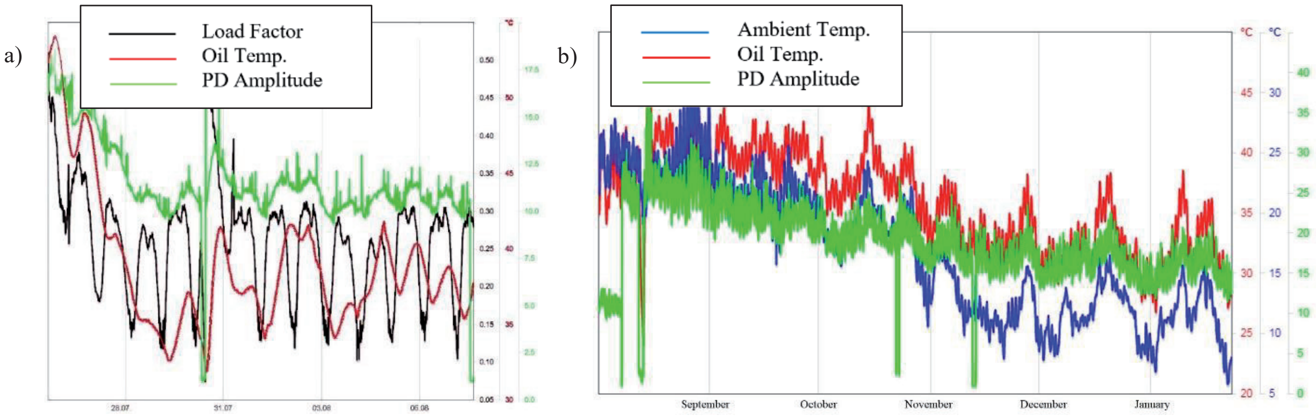

Fig. 14. Monitoring data a) 12 days b) 6 months

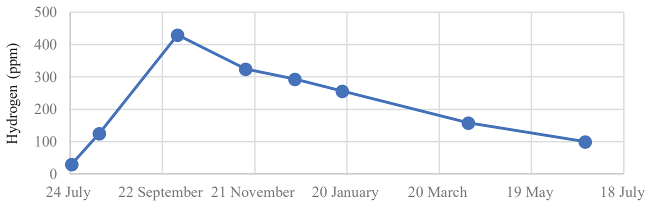

Figure 15 Development of hydrogen content

VII. Conclusions

Power transformers are critical to the reliability of the electrical power grid. Transformer failures result in significant damage and associated costs. All critical internal damage should be detected at an early stage. In addition to the standardized and widely used charge-based PD measurement in factory acceptance tests, it is advisable to consider electromagnetic PD measurement in the UHF range, particularly for assessing power transformers on-site and for continuous online monitoring. As per Cigré TB 861, UHF is recommended for both factory acceptance tests in conjunction with IEC 60270 electrical PD measurements and for permanent on-site PD monitoring. This recommendation stems from its advantages, including high sensitivity and reduced susceptibility to external disturbances.

Out of the two types of UHF PD sensors for power transformers introduced, the drain valve sensors can be installed in transformers equipped with standard DN50 or DN80 gate valves, whereas window-type UHF sensors are installed in dielectric windows provided on the transformer tank wall (meaning usually during construction of a new transformer). The former type is limited by the number and the location of available gate valves but can be used for retrofitting, while the dielectric windows can be placed on the transformer tank wherever desirable on new transformers.

An all-in-one UHF PD monitoring system was introduced, which can be used as a standalone PD monitoring or easily integrated in existing SCADA/monitoring systems using various protocols. It is one of the first UHF PD monitoring system which implemented the UHF calibration procedure recently published in Cigré TB 861. This procedure is needed to obtain two targets: to provide comparability and reproducibility of UHF measurement results from different systems and to incorporate any UHF sensor (with known antenna factor) into individual setups. The UHF calibration process consists of two different steps. The first step provides calibration factor K_M of the entire setup without the antenna The second must be performed by the antenna manufacturer, because the specific antenna characteristics of the UHF sensor (given by the antenna factor).

The positioning of UHF PD sensors on power transformers was discussed. In alignment with the proposal from Cigré TB 861, it is strongly recommended to place at least two sensors to achieve comprehensive and sensitive coverage throughout the entire tank. Additionally, using two sensors allows for performance checks. A reasonable setup consists of four sensors on the tank wall, facilitating UHF-driven localization. UHF installations are cost-effective, as they involve the installation of inexpensive valves or dielectric windows at the factory, with the option to add sensors later, as needed. The optimal sensor positions are near the outer limbs of the core, arranged diagonally on opposing sides of the tank wall, as they offer both sensitivity to UHF signals and a sufficient distance from the high voltage of the active part.

Three case studies of continuous UHF PD monitoring were presented. These studies exemplify the high sensitivity of the UHF method in three distinct scenarios and showcase the minimal noise and interference levels in UHF measurements at transformers in service. In terms of asset management, the examples highlight how PD monitoring can provide additional information to support decision-making processes. For instance, continuous PD monitoring can enable the continued operation of a transformer, even in cases where concerns exist about the equipment.

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