Partial Discharge Monitoring of Power Transformers by UHF Sensors

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Abstract — **The reliability of electrical energy networks depends on both, the quality and the reliability of its electrical equipment, e.g. power transformers. Local failures inside their insulation can lead to breakdowns and hence to high outage and penalty costs. Usually, power transformers are tested on partial discharge (PD) activity before commissioning. UHF PD monitoring can be used to prevent these events during service. Continuous monitoring exceeds the benefits of singular diagnostic measurements. Diagnostic PD measurements can provide snapshot information but no trend information. Also, temporary measurements can cause misleading interpretations due to the volatile nature of PD as measurements performed during low PD activity do not prove the general absence of PD. These drawbacks can be avoided by using continuous PD monitoring. In the first part, this contribution presents two different types of ultra-high frequency (UHF) sensors for PD measurement and their installation at power transformers including an UHF PD monitoring system. The second part is about a use case providing three years of UHF PD monitoring data of a power transformer, where the PD data is correlated with the transformer's load, temperature and the dissolved gas analysis.**

Keywords **— Power Transformers, Monitoring, Partial Discharge, UHF Sensors**

I. INTRODUCTION

Power transformers can be considered as an essential part concerning the reliability of the electrical grid. Hence, the reliable operation of power transformers is important for supply security because transformer failures tend to lead to significant damage with accordant costs. Therefore, all kinds of internal damages should to be recognized as early as possible. Different diagnostic methods have been established to meet the deriving demands for on- and offsite measurements [1]. Partial discharges (PD) measurement for example has been developed to detect local defects in the insulation that can be initiated and enlarged by the destructive nature of PD. Mainly, there are three different ways of PD monitoring: indirect detection by dissolved gas analysis (DGA), directly 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]. As DGA only provides an indication about PD being active, an increasing number of transformers are monitored using one of the direct measurement methods. 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 [4]. Its importance is accommodated by standardized electrical measurement according to IEC 60270 which is required for acceptance certificates at routine testing. The apparent charge Q_{IEC} has become an indicating factor for transformer quality. Especially in terms of monitoring and onsite diagnostic measurements, the electromagnetic UHF method gains in importance [5]. The electromagnetic emission of PD is measured using an UHF antenna which is inserted into the transformer tank. The generalized propagation paths of the methods are shown in Figure 1. Electrical signals travel through the galvanic coupling along the winding and are decoupled at the measurement capacity of the bushing (for online monitoring) or with an external coupling capacitor (not shown). Electromagnetic signals are not bound to the galvanic coupling and can radiate directly through the oil filled transformer. Usually, UHF PD measurements are shielded electromagnetically against external disturbances due to the Faraday shielding of the transformer tank [6] and low-pass filters provided by high voltage bushings. Therefore, UHF is less sensitive to external interferences compared to the electrical method. This creates an advantage for measurements in noisy environments, for example at on-site/online measurements and for monitoring. Cigré Working Group WG A2-27 recommends in brochure 343 to install DN50 valves in order to ensure highest flexibility for the later fitting of UHF probes. Alternatively, dielectric windows can be used for UHF sensors [7]. UHF sensors for installation at DN50 valves and dielectric windows are presented in the next chapter.

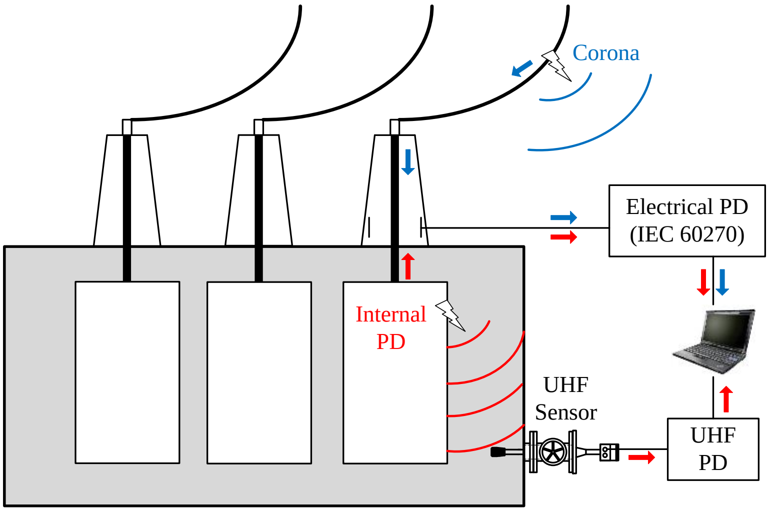

Figure 1 Signal propagation of UHF and conventional PD measurement at a power transformer with internal PD (red) and external PD (blue) [8]

II. UHF SENSORS

An UHF sensor for power transformers consists of a broadband antenna suited for the UHF frequency range radiated by PDs and of its mechanical adaption for the installation at power transformers. Mainly two UHF sensor technologies for internal PD measurement at transformers are used for practical applications.

a. UHF DRAIN VALVE SENSOR

An UHF drain valve sensor is designed as retrofit solution for transformers which have standardized DN50 or DN80 gate valves, see Figure 2 a). A standardized gate valve with straight duct where an UHF drain valve sensor can be installed is shown in Figure 2 b). Ball and guillotine valves can also be used for sensor installation. Figure 2 c) demonstrates a counterexample that is not suitable for drain valve sensor application. It illustrates a globe valve without straight opening. Other valve types without straight opening (diaphragm and butterfly valves) are also popular in some regions. As they are not applicable for UHF sensor installation, it is recommended to use only straight opening valves at new transformers.

Figure 2 a) UHF drain valve sensor for installation at standardized DN50/DN80 gate valves [9]
b) Gate valve as example for oil valves suited for UHF sensor installation
c) Globe valve as example for oil valves not suited for UHF sensor installation

Sensor application can be done even at transformers in service. At first, the UHF sensor is mounted on the valve. Secondly, the valve is opened slowly and de-aerated by a small ventilation valve on the sensor's mounting plate. Afterwards, the oil valve can be opened completely in order to insert the sensor into the transformer tank. The head of UHF sensor (the RF antenna) has to reach into the transformer for sufficient sensitivity. Usually, an insertion depth of approx. 50 mm has been proven as reasonable value. An installation of the RF antenna inside the pipe of the gate valve leads to low sensitivity due to electromagnetic shielding [3]. Besides sensitivity considerations, a minimum distance between UHF sensor and parts on high potential must be preserved to ensure save operation. UHF drain valve sensors are mainly used during diagnostic measurements on-site because their design allows them to be installed at power transformers in service. Nevertheless, permanent installation as part of an online PD monitoring system is possible as well.

b. UHF Plate Sensor

UHF plate sensors as shown in Figure 3 a) can be mounted directly to the tank wall which is suitable e.g. for newly built transformers. A dielectric window is integrated into the tank wall. It consists of a stainless-steel welding ring and a high-performance plastic which resists mineral oil and high temperatures. The plastic has a permittivity similar to mineral oil which allows UHF signals to pass through to the UHF sensor with low damping. The plate sensor is mounted into the dielectric window. Its RF antenna reaches into the transformer tank through the window that acts as oil barrier. In contrast to the drain valve sensor, plate sensors allow UHF measurements and sensor swapping without oil handling. Figure 3 b) shows a dielectric window and welding ring for installation at transformer tank walls. Plate sensors can be included into the transformer tank at any suited position. Even if no sensors are installed at the delivery of a transformer, oil-sealed dielectric windows with a blank cover can be mounted onto the tank wall during production to allow an easy retrofit of UHF PD monitoring during service. In Figure 3 c), a test installation of three UHF plate sensor prototypes at a power transformer is shown.

a) b) c)

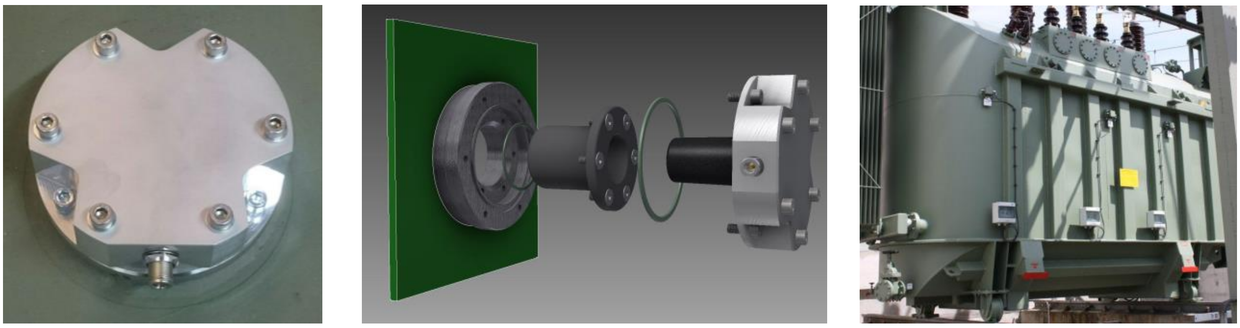

Figure 3 a) UHF plate sensor for direct installation at transformer tank wall [9]
b) 3-dimensional drawing of welding ring (left), dielectric window with gasket (middle) and UHF plate sensor (right) [9]
c) Test installation of UHF plate sensor prototypes at a power transformer

III. UHF Monitoring System

This chapter presents a synchronous 4-channel UHF monitoring system which can be used to either monitor one transformer with up to four UHF sensors or up to four transformers with each only one UHF sensor in a substation. Figure 4 shows the monitoring system with one UHF drain valve sensor installed at a transformer.

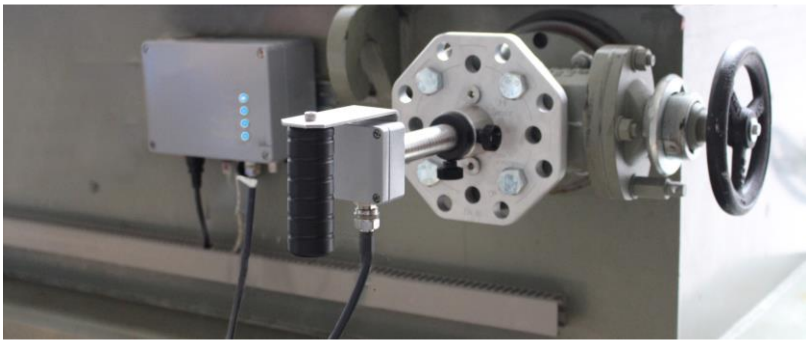

Figure 4 UHF monitoring system installed at a transformer with UHF drain valve sensor at a DN50 gate valve

The 4-channel monitoring system uses a vertical resolution of 12 bit per channel. It is able to synchronously detect UHF signals between noise level at approx. U_{noise} = 1 mV and U_{max} = 2000 mV at all 4 channels. The phase resolution in 50 Hz and 60 Hz systems is $\varphi = 1°$. Therefore, detailed phase resolved partial discharge patterns (PRPDs) can be recorded for expert evaluation [10]. A trend view of UHF amplitude and PDs/min is provided for long term evaluation and correlation with other measured values (voltage, load, temperature). A more detailed trend view can be used for tracing of PD patterns: a time-resolved PRPD pattern allows recognizing changes in PRPDs in direct correlation with other measured values. A description of this time-resolved PRPD including example is given in the next chapter.

The UHF monitoring system is connected to a server or a desktop PC via Ethernet for storage and evaluation. The monitoring system can be accessed easily by a graphical user interface (GUI) used for system parametrization (including alarm/warning thresholds) and visualization of the measured real-time data. Figure 5 shows a screenshot of the UHF PD monitoring GUI. Real-time UHF PRPDs (left) and trend views (right) of two UHF sensors are presented. All diagrams can be parametrized and exported into standard images (jpg-files) either for single measurements or periodically (e.g. a snapshot can be exported every hour). Alarm thresholds can be defined for signal amplitude and counted PDs per interval. The trend data can be exported to csv-files for post-correlation with other operational data (e.g. on load tap changer (OLTC) position). There is also the option to reimport historical trend data for replay and PRPD generation. The provided toolset can assist asset managers to surveil and evaluate the actual status of transformers in service. It also helps PD experts for a better understanding of PD failures by continuous observing of PD and possibility of correlation to other measured data.

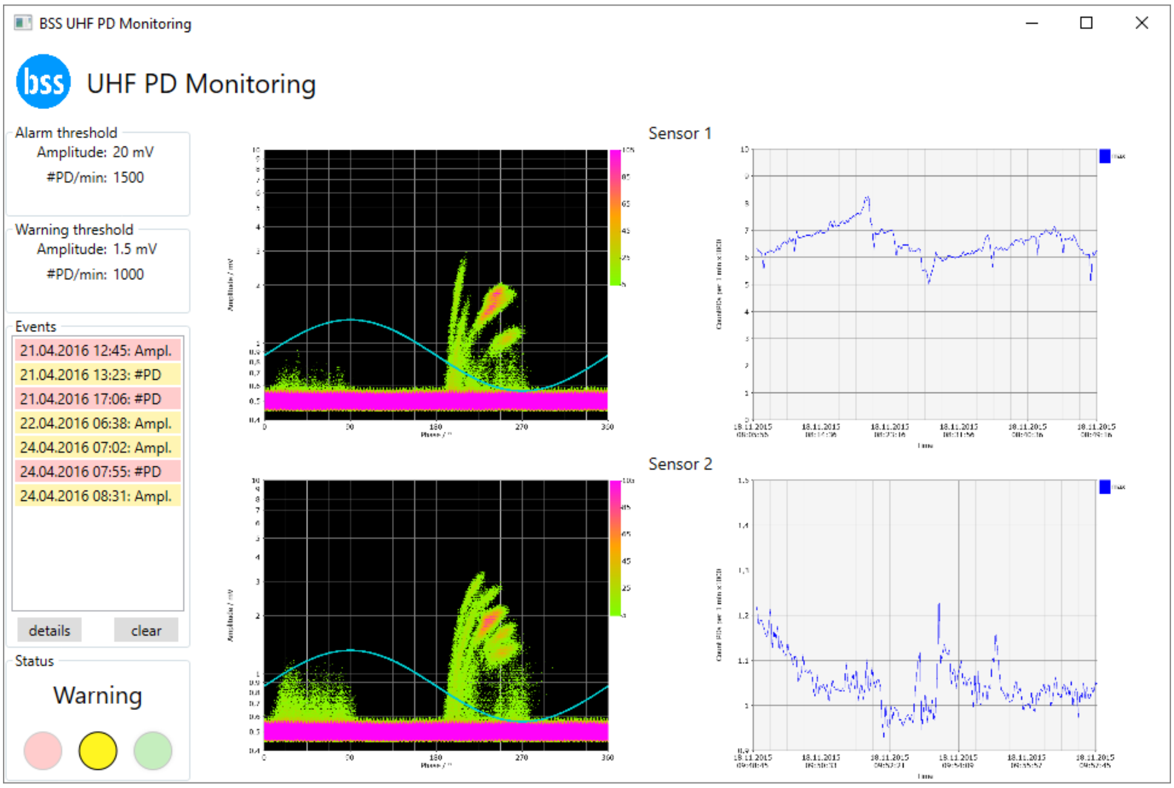

Figure 5 GUI of UHF PD monitoring software with real-time visualization of PRPD and trends (screenshot) [8]

IV. USE CASE: 120 MVA GENERATOR STEP-UP-UNIT

This use case presents PD monitoring data of an approx. 50-year-old unit generator transformer with 110/10 kV rated voltage and 120 MVA rated power, which is by now monitored for more than six years. Prior to this, the transformer was out of service for 8 years. A condition assessment before bringing the unit back into service indicated PD: conventional PD measurements according to IEC 60270 were performed using external coupling capacitors. PRPD patterns indicated that the transformer has more than one active PD at nominal voltage.
Due to the lack of common rules and threshold values for aged transformers, it was decided that the unit can only be put back into service if it is monitored continuously. For permanent observation of PD data, an online UHF PD monitoring system with an UHF drain valve sensor was installed. Furthermore, voltages, load currents, top-oil/ ambient temperatures, mechanical vibrations and dissolved gases (using a Hydran sensor) were recorded. The PD trend is used as indicator if the insulation defects are getting worse. PRPD monitoring data confirms the presence of more than one PD source. The PDs are not present permanently at constant voltage conditions. As the measured PDs show no clear trends, alarm thresholds are set slightly over the "normal" PD behavior. Alarm parameters are given by the maximum signal amplitude of UHF PD (in mV) and by the counted PD events per minute.

The following represents a case with exceeded alarm levels. Figure 6 a) shows a UHF PRPD pattern and Figure 6 b) PRPD data over time whereas the color gradient in a) represents the number of recorded PD per minute and in b) the UHF amplitude in mV.

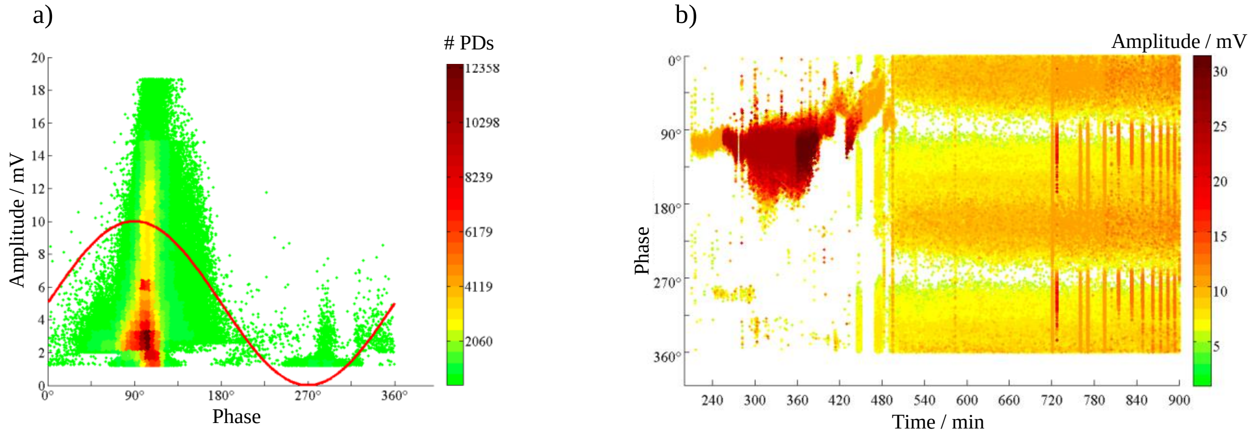

Figure 6 a) UHF PRPD (240 min – 420 min in b))
b) 2-dimenisonal simplification of time domain PRPD (no #PDs shown)

The UHF PRPD pattern in Figure 6 a) shows the PRPD data from Figure 6 b) 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 the observation of the event, the amplitude and number of PDs stayed constant and did not worsen so it was decided to keep the transformer in service. After 3 h of high amplitudes, the PD event vanished and PD activity normalized. The measured combined dissolved fault gases represented by the Hydran value started to increase approx. 4 h after the PD event was over. Figure 7 shows the trend view of the PD amplitude correlated to the Hydran value.

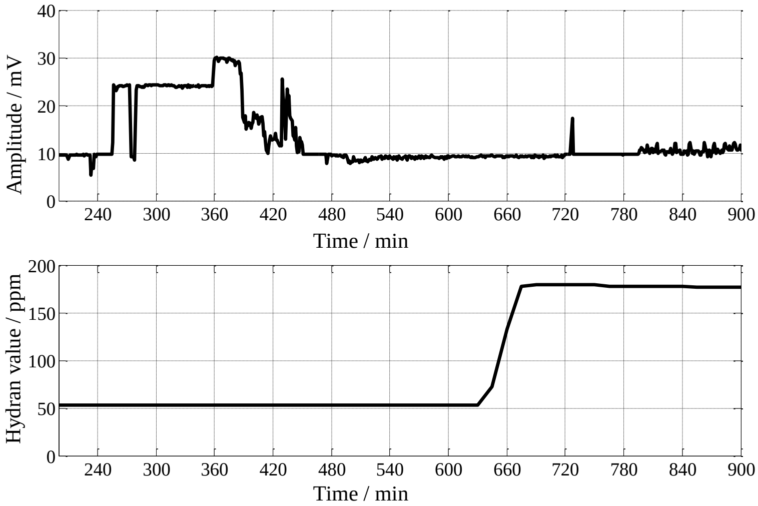

Figure 7 Max. UHF PD value (in mV) correlated with Hydran value (in ppm)

The alarm threshold for the fault gas value was exceeded approx. 7 h after the PD event started. This delay between generating H_2 and the increased values at the gas sensor is due to the gas solubility and dispersion in the transformer. This example shows the advantage of direct PD monitoring. The UHF PD monitoring system gives a real-time alarm in case of PD events and the PD can be observed using PRPDs and trend views. In contrast, the DGA monitoring only gives an alarm with several hours delay (in this case) and no detailed information about the PD itself.

V. CONCLUSION

Partial discharge measurement is common practice for transformer type tests and diagnostic measurements. It represents a suitable tool to detect local defects in the insulation before these defects can emerge to a breakdown. Hence, the method suggests itself for asset management in terms of continuous monitoring. Monitoring exceeds the benefits of conventional diagnostic (singular) measurements. Diagnostic PD measurements can provide snapshot information, but do not provide any trend information. Also, temporary

measurements can cause misleading interpretations due to the volatile nature of PD as measurements performed during low PD activity do not prove the general absence of PD. These drawbacks can be avoided by using continuous PD monitoring.
PD can be detected directly by electrical, standardized PD measurements according to IEC 60270 or by UHF measurements using antennas. The UHF method is advantageous for monitoring of on-site/online transformers, because UHF sensors are not galvanically coupled to the high voltage, do not require bushing measurement taps and are less affected by external PD sources (e.g. corona at bus bars). Sensors can either be applied at transformers online/on-site using UHF drain valve sensors at DN50/DN80 valves or at new/refurbished transformers at the factory using UHF plate sensors with a dielectric window.
A case study illustrates PD monitoring at a generator step-up unit in combination with gas-monitoring over several years. Long-term evaluation proves PD being highly volatile. A severe rise of fault gases correlates with a significant gain in PD activity which caused both monitoring systems to raise alarms. The systems differ in their alarm delay: the PD alarm was triggered 7 hours earlier than the gas alarm (due to the high time constants of dissolving gases). Hence, a combined monitoring is considered as ideal asset management. PD monitoring can provide the fastest response times. Correlations, e.g. with gas measurements, can be used to affirm the transformer's status. After such an incident, the historical databases of monitoring systems can help asset managers and experts to decide the next steps.

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