Review of Online Partial Discharge Measurement Practices

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1. Introduction

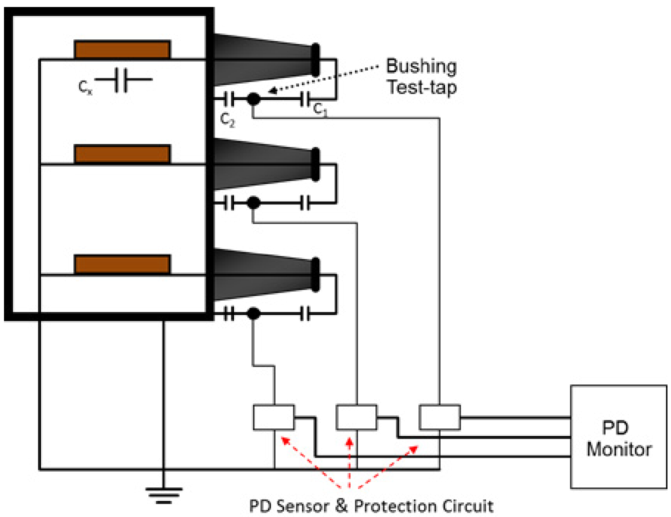
Because partial discharge (PD) activity is often present well in advance of insulation failure, it provides the most evident indication of defects and deterioration. Asset managers can evaluate PD activity over time and make informed strategic decisions regarding the timely repair or replacement of the equipment before an unexpected outage occurs.

For decades, PD measurement on transformers has used either radio influence methods (RIV) calibrated in micro-volts according to NEMA 107, or wide-band or narrow-band PD detectors calibrated in pico-coulombs according to IEC publication 60270. Unconventional PD measurements like ultra-high frequency and ultrasonic (acoustic) PD measurements are increasingly being used. However, there are no accepted procedures or guidelines available for unconventional PD measurement methods, as has been the case for conventional methods for several decades. There are many open issues concerning unconventional PD methods including: calibration or sensitivity verification procedures, techniques for noise suppression, and methods of fault location, etc.

This review compares the conventional and unconventional PD measurement practices not only with respect to the physics and method of measurement but also on the open issues previously described and practical aspects that must be considered when implementing them.

2. Conventional Electrical PD Measurements

According to IEC 60270 and IEC 60076-3, the preferred setup to measure apparent PD charges is shown in Fig. 1. For clarity, only three HV bushings are being monitored in the example.



- The bushing C_1 capacitance acts as a coupling capacitor to decouple high frequency PD pulses both from a source inside the transformer tank and from outside the tank (external sources).
- For bushings without a capacitive tap, an external coupling capacitance is connected in parallel with the bushing.
- The PD measurement system is connected to the sensors via co-axial cables.

Fig. 1: Principle of Conventional PD Measurement (image courtesy of Raja Kuppuswamy)

With conventional PD measurement (IEC 60270), the apparent charge is measured in pC which is the integrated current pulse, caused by a PD, which flows through the test circuit. The conventional method allows a precise calibration but requires a sufficiently high signal-to-noise ratio (SNR) in the measurement circuit to easily resolve the PD signal in question. The standardized method of IEC 60270 has been practiced since the 1960s and is well regarded.

PD pulse amplitude, PD pulse trend and phase-resolved PD (PRPD) patterns are well known to correlate with the extent of insulation damage. Reference PRPD patterns are widely available for different discharge defects and for different high voltage components, which is another significant advantage of conventional measurement.

The unique advantage of conventional PD measurements is that the charge content in a PD pulse can be related to a known reference. Phase-resolved PD patterns are widely available for different discharge defects and for different HV components. Therefore, it is widely used during factory and on-site transformer PD Testing.

For factory transformer PD acceptance testing, IEC 60270 imposes lower and upper limits on the measurement frequency. The primary goal is to have uniformity in the transformer PD testing process across different laboratories so that results can be compared against a pass / fail criterion (e.g. 500pC).

Factory testing is performed inside Faraday-cage styled shielded laboratories with PD-free connections and terminations. This isn't practicable for PD measurements on in-service transformers, which are exposed to a variety of 'noise' sources outside the tank. Examples of such 'noise' sources would be inadequate corona shielding of line terminals, bad or loose connections, PD from other interconnected HV systems, or arcing from the transmission line. Several established procedures are available to suppress these interferences to make on-site noise free PD measurements.

3. Ultra High Frequency PD Measurements

Principle of Measurement

The principle of ultra-high-frequency (UHF) PD measurement is illustrated in Fig. 2. The electromagnetic emission from a PD source is measured using an UHF antenna which is inserted into the transformer tank through an oil-sampling valve. The metal surface of the transformer tank acts as a natural Faraday-cage to filter out electrical interferences from outside the tank. High Voltage bushings' C1 capacitance acts as a low-pass filter to reduce electrical interferences from outside the tank. These advantages make it suitable for measurements in noisy environments, e.g. on-site / online measurements and monitoring.

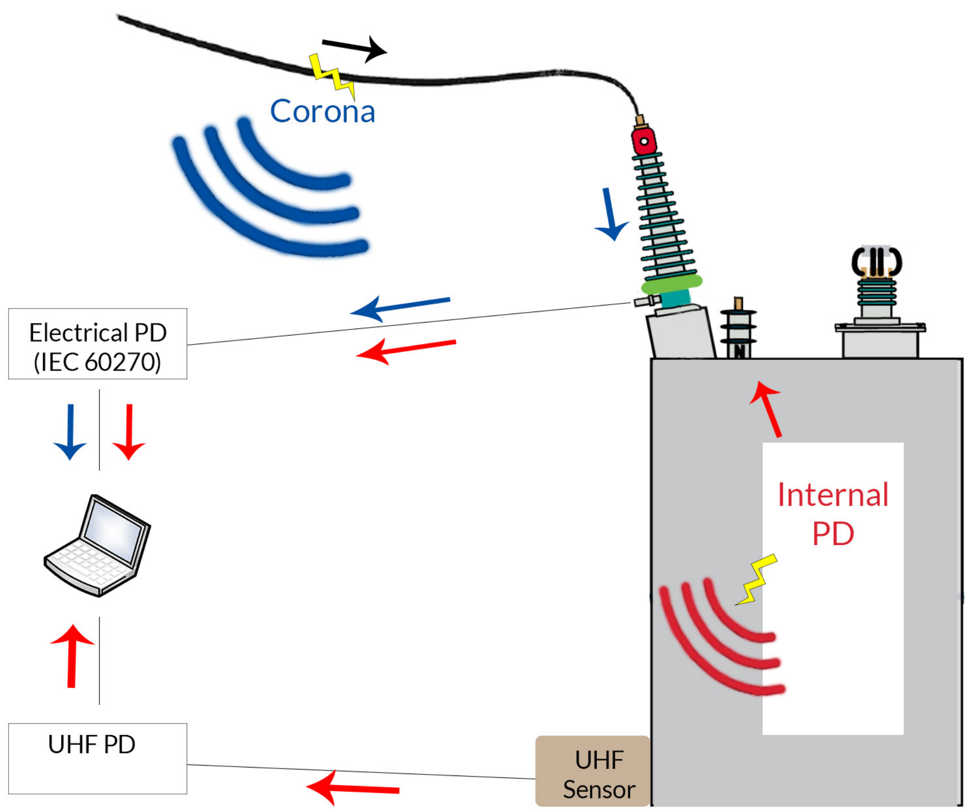


Fig. 2: Principle of UHF partial discharge measurement

The 'faraday-cage effect' of the transformer tank and the filter function of the high voltage bushings makes UHF PD Measurements less sensitive to electrical interferences from outside the tank.

UHF measurement is based on the common assumption that PD takes the form of fast rise-time electrical impulses which radiate electromagnetic (EM) waves with frequencies up to the ultra-high frequency range (UHF: 300 MHz to 3000 MHz). Investigations by the author [1] show that high frequency current flowing through the metallic parts of the transformer (e.g. winding), transforms the metal surface to an emitter of EM waves, therefore they are the source of the EM emission and not the PD source itself. In general, the radiation behavior of UHF PD sources is more complex and only partially understood.

Commonly Used Forms of UHF PD Measurement Antennas (Probes / Sensors)

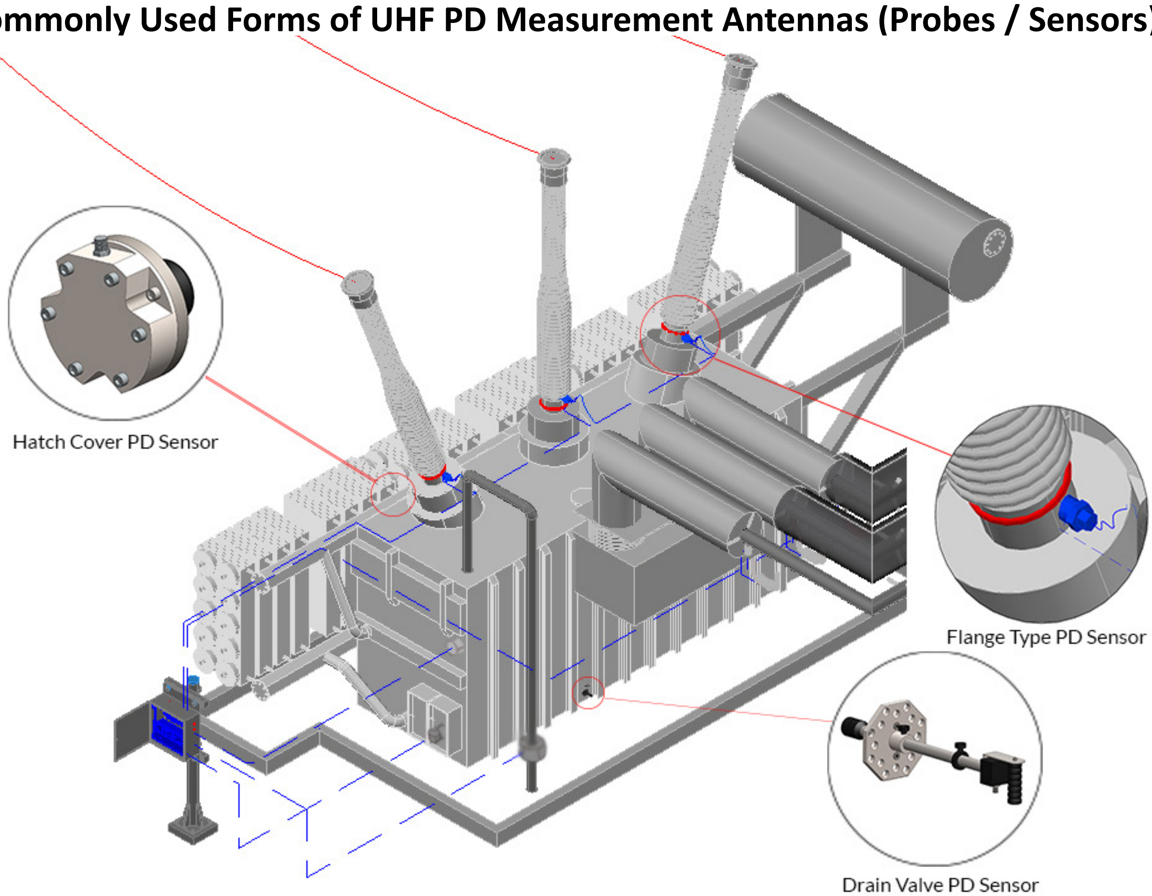


Fig. 3: Three forms of UHF PD measurement probes used in transformer monitoring

Oil (drain) valve UHF PD probes are designed for use inside straight-opening oil-filling valves of at least 1.5” in diameter. This design has several restrictions. The design requires by default, straight opening oil valves, which are not common. The method of use requires the UHF probe head to stick-out horizontally from the inside wall of the tank by at least 2 inches or ~5cm. Because of the probe head’s close proximity to the windings under voltage, its location requires careful selection to avoid compromising the safety of the transformer. In some transformer designs, oil-flow guiding tubes are present behind the valve openings (inside tank), which limits the depth to which the probe heads can be inserted. The depth of the probe head and antenna design has a significant effect on the PD measurement sensitivity.

Hatch cover type UHF probes are designed for use inside dielectric windows custom fitted directly onto the transformer tank wall or onto the hatch cover plates. This requires a circular slot cut in the hatch cover plate to insert the dielectric-window. The UHF probe sits inside the slotted window. This procedure requires an outage on the transformer and oil drainage up to a level below the hatch cover plate. This installation procedure is not suitable for transformers operating in service due to practical constraints in implementing this on site and the risk of exposing the internal parts of the transformer to the atmospheric air.

Flange-type UHF sensors are designed to fit snugly around the lower shed of the high voltage bushings. Due to its use outside the transformer, they are vulnerable to external electrical interferences.

Hatch cover type and flange-type UHF probes are installed outside the transformer tank and do not benefit from the Faraday-cage shielding effect from noisy sources outside the tank.

UHF PD Measurement Sensitivity

Overall sensitivity of UHF PD measurement is influenced by factors listed below:

- The structural design, dimensions and materials used in the UHF Antenna construction.
- Depth of the probe head or dielectric window inside the tank wall
- Distance between the PD source and UHF Antenna.
- Presence of obstacles between the UHF antenna and PD source. Depending on the material (metal / dielectric), thickness and orientation of the obstacle the amount of EM waves reaching the antenna varies greatly.

For reliable detection of PD sources in large power transformers, it is essential that EM waves emitted by PD can be measured everywhere inside the transformer with minimal loss of UHF energy. Empirical studies [2] on 210 MVA grid coupling transformers have shown that attenuation varies between 2.0 dB/m (~20 % loss) to 6 dB/m (~50 % loss). 2.0 dB/m is when there is no obstacle between the PD source and probe, and 6.0 dB/m when there is an obstacle in between.

Limitations

One of the commonly asked questions during PD measurement is which phase-winding(s) is/are affected. This question cannot be answered without any ambiguity as the EM waves captured by the UHF PD antenna cannot be uniquely related to any phase-winding.

Another disadvantage is that UHF PD readings cannot be calibrated in terms of apparent pico-coulombs as in the IEEE or IEC standards on factory PD acceptance testing of transformers. The inability to relate field PD measurements to factory reference measurements to evaluate the extent of damage is considered as a significant disadvantage by users of UHF PD measurements.

The major disadvantage is that UHF PD readings cannot be calibrated in terms of apparent pico-coulombs as described in IEEE / IEC Standards on factory PD acceptance testing of transformers.

Since UHF PD detection equipment operates at higher frequencies, and the required components are expensive, the test equipment is often more expensive than conventional PD detection systems.

4. Ultrasonic (Acoustic) PD Measurements

The main purpose of permanently installed online acoustic monitoring systems is to provide an early indication of an incipient fault to a remote location which can then be followed by more extensive field tests. Common industry practice is to perform these measurements in response to abnormal gas-in-oil test results or sounds that may indicate partial discharges.

Active PD sources in oil-filled transformers produce acoustic emission signals that propagate away from the source in all directions. The acoustic signals travel through the intervening material to eventually arrive at the transformer tank wall. The distance traveled is dependent on the time that it takes for an acoustic signal to complete this journey as shown below.

distance traveled = acoustic wave speed x time

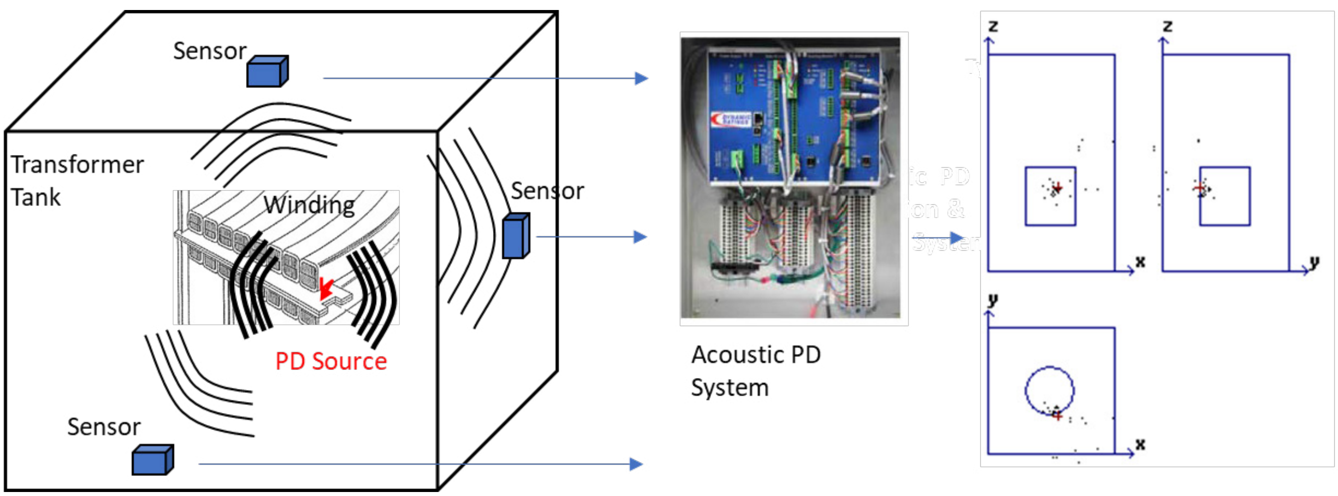


Fig 4: Principle of Ultrasonic (Acoustic) PD Measurement. Drawing (left) and screen shot (right) courtesy of Raja Kuppuswamy.

Consequently, sensors placed at different locations on the tank wall, i.e. at different distances from the source, will experience different signal arrival times. The signal arrival times are then used to determine the position of the PD source inside the tank. There are two general categories of acoustic location systems: all-acoustic systems and acoustic systems with an electrical PD trigger.

The first category, the all-acoustic system, consists of one or more ultrasonic transducers that are sensitive to the acoustic emissions generated by a PD event. The detection and coarse location of one or more sources can be accomplished by moving one sensor around the transformer. A more precise location of a PD source may be determined by the relative arrival times of the acoustic signals at each of the sensors. No voltage or current readings are required on the transformer. This makes the all-acoustic system a suitable tool for source location on operating transformers in the field.

The second category, the acoustic system with an electrical PD trigger, pairs the array of acoustic sensors described above with a current or voltage measurement device that detects the PD signal electrically. Since the electric signal is detected instantaneously, the arrival time of the electric signal can be used as time zero for the PD event. The difference in arrival times of the electric signal and an acoustic signal is the propagation time between the PD source and that sensor location. Thus PD location in this type of system is based on the absolute arrival time at each sensor, as opposed to the all-acoustic system described above which uses the difference in arrival time between sensors.

Signal sensitivity is unique to each acoustic monitoring system. The general experience has been that the following PD sources can be generally identified: PD sources outside the winding, arcing or tracking of the bushing surface in oil, PD inside the tap-changer and very high intensity discharges within windings. Discharges within windings, inside HV bushings and acoustic signals produced by gas bubbles are usually difficult to detect. Weather (rain, snow, sleet, hail, lightning strikes) and mechanical disturbances created within or outside the tank (core magnetostriction, pumped liquid noise, loose shielding connections inside the tank wall, loose name plates, fan noise, etc.) also interfere with the measurement. Apart from these factors, how the sensor is placed on the tank, shielding used inside the tank wall, and insulating barriers between the sensor and fault source have a significant effect on the measurement sensitivity.

Acoustic detection has several advantages compared to other techniques, it is immune to electromagnetic interferences and can be used to locate the PD activity. However, the acoustic signals suffer from high attenuation which makes the detection of PD activity a difficult task.

There are also lesser known factors that affect the measurement location accuracy that are described in [3]. For example, the angle formed between the sensors and the PD source can have a significant effect on the measurement location accuracy as illustrated in [3].

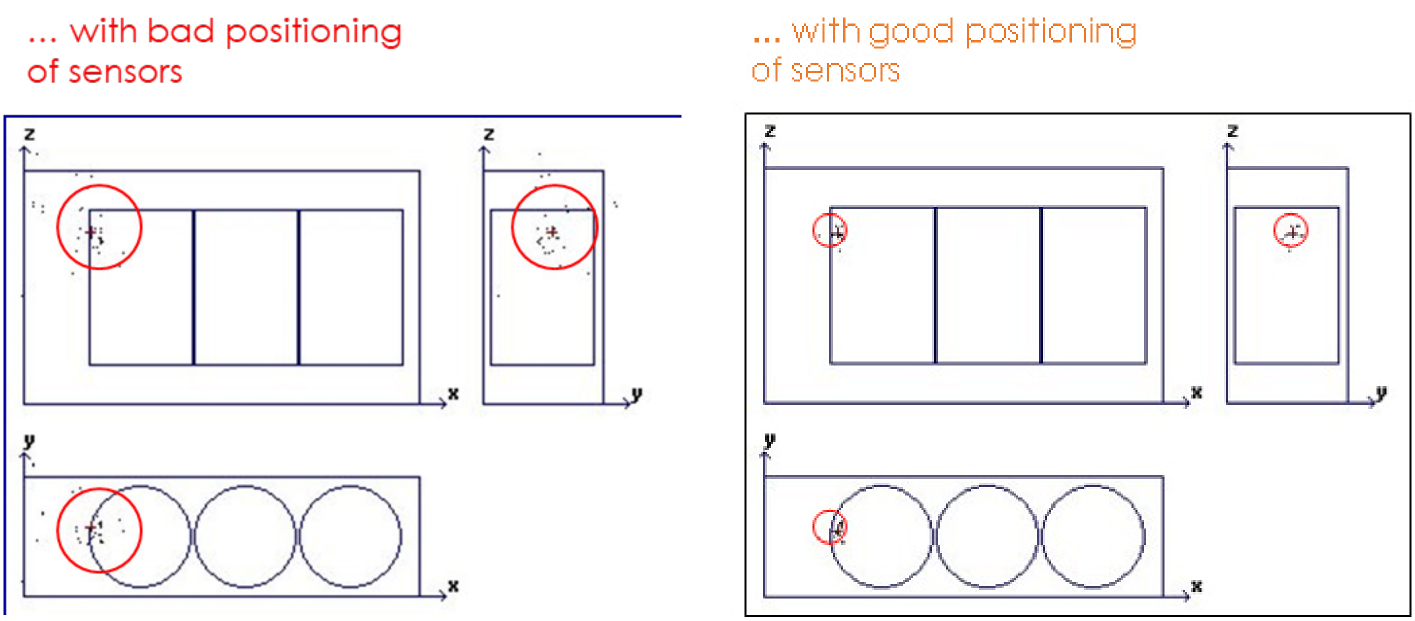


Fig 5: Illustration of the effect of bad and good positioning of sensors on the accuracy of fault location. Image courtesy of Raja Kuppuswamy. [3]

5. Comparison of PD Measurement Techniques

KEY DIFFERENTIATORS	CONVENTIONAL	UHF	ACOUSTIC
Immunity from electrical noises without noise filters	Low	High	High
Immunity from mechanical noises	High	High	Low
Measurement Sensitivity	High	High	Low
Geometric Location of PD Sources	No	No	Yes
PD calibration as per IEEE & IEC factory testing standards	Yes	No	No
Availability of reference PRPD patterns for different PD defects and HV components.	Yes	No	No
Identification of defect type using phase-resolved PD patterns	Yes	No	No
Used during factory transformer acceptance testing	Yes	No	No

Table 1: Comparison of PD Measurement Techniques

6. References

1. Raja Kuppuswamy, F. Devaux, S. Lelaidier, “Some Fundamental Observations during UHF Partial Discharge Measurements on Power transformers”, 2003 CIGRE Transformer Colloquium, Mexico.

2. S. Coenen, S. Tenbohlen, S. Markalous, T. Strehl, “Fundamental characteristics of UHF PD probes and radiation behavior of PD sources in power transformers”, 16th International Symposium on High Voltage Engineering, Cape Town, South Africa, 24-28 August 2009, pp. 666-671.

3. Raja Kuppuswamy and Stephan Lelaidier, “A novel technique for estimation of accuracy of location of partial discharges in power transformers, 2002, International Conference on Electrical Insulation, St Petersburg, Russia.

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