TLM

TRANSFORMER-LIFE-MANAGEMENT
CONFERENCE

# Acoustic and electrical methods combined for localizing partial discharge in power transformer


## Stefan M. Hoek, Omicron Austria


Stefan Hoek is Product Manager for partial discharge measurement system and joined OMICRON, Austria in 2008. He studied electrical engineering at the University Stuttgart (Germany) and worked there as research assistant with focus on partial discharge detection and localization in GIS with help of measurements in the UHF range. Stefan Hoek is member of VDE ETG and CIGRE working group B3.24 and published several papers.

OMICRON

TLM

TRANSFORMER-LIFE-MANAGEMENT
CONFERENCE

# Acoustic and electrical methods combined for localizing partial discharge in power transformer

## ACOUSTIC AND ELECTRICAL METHODS COMBINED FOR LOCALIZING PARTIAL DISCHARGE IN POWER TRANSFORMER

Stefan M. Hoek[1*], Alexander Kraetge[1], Michael Krüger[1], Stephan Körber[2], Ole Kessler[2], Rene Hummel[2], Ulrike Broniecki[3]
[1]OMICRON electronics, Austria, [2]OMICRON energy solution, Berlin, [3]Berlin University of Technology, Germany,
*Email: stefan.hoek@omicron.at

**Abstract**: The reliability of electrical systems depends on the quality and availability of the power apparatus. Power transformers are important nodes in the electrical power grid. Common reasons for breakdown are problems in the insulation system. Detecting partial discharges in the insulation system of a power transformer at an early stage reduces the risk of total breakdown. One method to detect partial discharges is acoustic measurement. With this technique detection and localization of partial discharge is possible by placing acoustic sensors on the surface of the transformer tank. The low level of electrical interferences from outside the measurement setup constitutes one of the strengths of this method. A further advantage is the ability to identify the position of the partial discharge source, which is needed to estimate the risk and to enable a fast and effective repair.

### 1 INTRODUCTION

Partial discharge (PD) measurements on transformers are an accepted tool of quality control in factory and on site. Different PD measurement techniques are using a variety of different physical characteristics of the PD phenomenon, e.g. electric discharge currents (acc. to IEC 60270 [1]), gas formation (DGA - dissolved gas analysis), electromagnetic (UHF Measurement) or acoustic radiation. The main benefits of an acoustic PD measurement are the possibility to detect PD without a shut-down of the transformer, and the ability of localizing a PD source with an accuracy of a few centimeters to a few decimeters. In case of expected PD, an acoustic PD measurement can help to verify it, while the location is important information for further risk assessment and repair planning.

### 2 THE PROPAGATION BEHAVIOR OF ACOUSTIC PD SIGNALS IN TRANSFORMERS

The acoustic effect of PD inside a transformer is typically measured by piezo-electrical sensors in the frequency range of tens of kHz up to hundreds of kHz [2]. Using the different arrival times of the acoustic PD signal at multiple sensors, algorithms can compute the location of the PD source.
The complex physical processes involved in sound propagation and the large structural variety of different transformer may present a challenge during the measurement. The following parameters have to be considered:

- The PD source position and the inner structure of the transformer mainly influence the propagation path of the acoustical waves.
- More than one propagation path from the PD source to a sensor is possible (direct oil, reflection, steel path).
- The speed of sound depends on the propagation path (crossed medium), frequency and temperature.
- Depending on the location of the source and the inner structure of the transformer, a proper measurement of the direct oil path signal may be impossible due to high signal attenuation.
- Taking into account the individual measurement setup and the inner structure of the device under test (DUT), a cautious interpretation of the measurement results by an experienced person is essential.

Speed and damping of the acoustic waves are dependent on the transfer medium, frequency range and temperature [3], [4]. For example, the propagation speed decreases during the heat-up period of a transformer by approximately 15%, from about 1400 m/s at 20 °C to 1200 m/s at 80 °C. This has to be considered to avoid miss-localizations since the signal speed directly influences the calculated results.

The propagation path is often complex. Multiple propagation paths of the emitted sound wave are possible, as shown in Figure 1. Depending on sensor and PD location, multiple acoustic wave components of the same PD event are potentially detected by one sensor and overlay the direct oil signal as illustrated in Figure 2. The acoustic wave can be reflected by the tank wall, core, winding, flux shields and other components.

# Acoustic and electrical methods combined for localizing partial discharge in power transformer

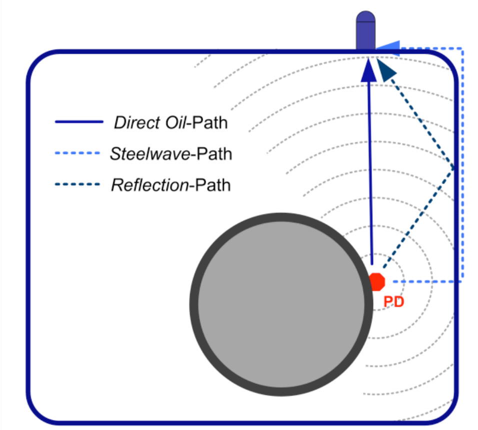


**Figure 1:** Possible propagation paths in the test object [5]

Components of the reflected wave will arrive at the sensor position later than the signal travelling a direct path. Furthermore, the acoustic wave can couple into the transformer wall and propagate through the steel of the tank. Due to the higher propagation speed in steel of about 3.000 - 5.000 m/s [2], the so-called steel wave signal can reach the sensor earlier than the waves following the direct oil path. This effect complicates the automated determination of the starting point of the direct oil signal.

The measurable direct oil signal at the sensor position depends on the intensity of the causative PD event [6] and on the damping on the propagation path. Therefore, the attenuation by core, winding, transformer board, flux shielding etc. should be as low as possible. For that reason, the search for sensor positions that ensure good signal quality is essential during measurement procedure. The knowledge about the inner structure of the transformer is helpful for a good positioning and repositioning of the sensors.

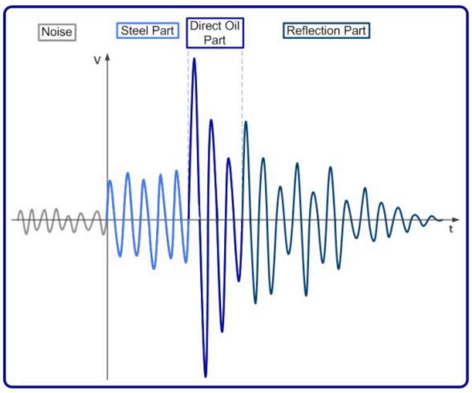


**Figure 2:** Acoustic PD signal components reflecting the propagation paths

## 3 LOCALIZATION OF PD

Different algorithms can be used to perform a time-based localization of PD. The input information used by the algorithms is the time of arrival of the signals propagating on direct oil paths to multiple sensors. The exact time of arrival has to be determined by evaluating the measured signal. A criterion for the starting point can be found e.g. by investigation of energy steps [7] or by threshold criteria [8].

The relative arrival times at different sensor positions lead to time differences ($\Delta t_{1,2}$). These time lags are the only available data in all-acoustic measurements, when the data acquisition is triggered by the acoustic signal at one of the sensors. If the time delay between occurrence of a PD and the arrival of the associated acoustic wave is available, the absolute propagation times ($t_1$, $t_2$) from source to sensor can be used for localization. Both principles are shown in Figure 3.

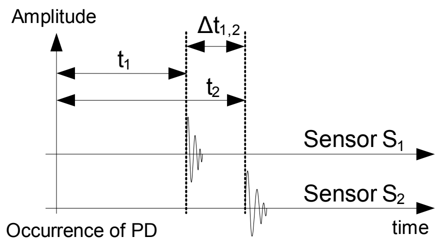


**Figure 3:** Absolute and relative times in a two-sensor-setup

The exact timing of the emission of the PD signal can be estimated e.g. by an electrical PD measurement according IEC 60270 or a measurement in the ultra-high frequency (UHF) range. In the latter case, sensors within the transformer walls can be used to receive the high frequency electromagnetic wave that is emitted during PD [9]. A measurement setup is shown in Figure 4 [10].

**Figure 4:** Installed UHF probe

# Acoustic and electrical methods combined for localizing partial discharge in power transformer

The distance between sensor and source is calculated using the available absolute or relative propagation times and an estimated average propagation speed. With the determined distances and the sensor positions a geometrical localization of the PD source can be performed in several steps (Figure 5)

The arrival time ($t_1$) at a single sensor in relation to the PD occurrence leads to a surface in the shape of a sphere around the sensor position on which the PD source is supposedly located. The radius r depends on the absolute propagation time ($t_1$) and the propagation speed (Figure 6 left)

In all-acoustic measurements the data of a single sensor (without a relation to another sensor signal) does not contain information leading to a triangulation. In this case the data of two acoustical sensors - the relative time $\Delta t_{1,2}$ – deliver a distance difference ($\Delta d_{1,2}$) and therefore a hyperbolic sphere (Figure 6 right).

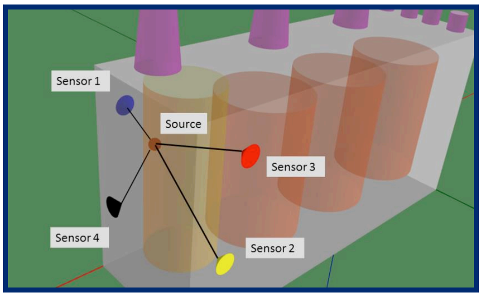


**Figure 5:** Principle of acoustic localization [5]

The position of the source can be specified with the information from a higher number of sensors. For this purpose several of the described geometrical shapes are intersected. The absolute propagation time of the signal at a second sensor leads to a second sphere, the resulting intersection shape is circular. In a further step the absolute coordinates of the source can be estimated by intersecting the circulars of three sensors.

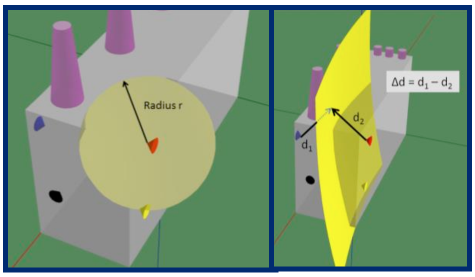


**Figure 6:** Spatial information from one absolute time ($t_1$) and from one relative time ($\Delta t_{1,2}$)

This procedure is shown in Figure 7. The figure shows the spheres around three acoustic sensors (black, yellow and blue). The resulting intersection circulars of the spheres are shown as blue rings. The estimated point of the acoustic source is displayed for three or more acoustic sensors like in Figure 15.

In an all-acoustic measurement environment the approach is in principle identical. In this case a fourth sensor delivers the necessary information to estimate a point representing the origin of the PD signals.

The depicted method is based on a direct propagation path for the acoustic wave from source to sensor. As described above, the transformer cannot be considered as an empty box and the propagation speed is highly dependent on the signals travel path. For that reason, the model is always a simplification of the real setup inside the tank. Thus, also an inaccurate localization of the source position is possible.

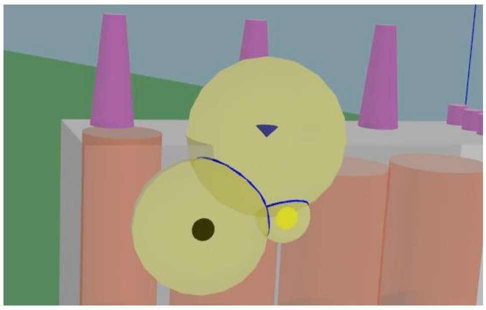

**Figure 7:** Source localization with three sensors using absolute times

To ensure reliable measurement results, a workflow is proposed that is based on an iterative relocation of the sensors with the intention to find positions with a minimal and undisturbed path between sensor and source.

## 4 CASE STUDIES OF SUCCESSFUL ACOUSTIC PD FAULT LOCALIZATIONS ON TRANSFORMERS

### 4.1 PD localization on a 16 MVA transformer using electrical PD signals as trigger source

The described investigation has been performed on a 150 kV/20 kV three-phase power transformer (Yyn0) with a nominal rating of 16 MVA. Figure 8 shows the electrically measured PD pattern of phases V and W indicating a PD problem nearby phase W. Consequently the acoustical sensors were placed on the tank walls close around the suspicious winding. After analyzing the first results, the sensor positions have been optimized. Two sensors had to be placed on top of the transformer housing because of limited accessibility due to the assembled coolers. Figure 10 shows the tested transformer, modeled in the software of the location system and the finally used sensor positions.

# Acoustic and electrical methods combined for localizing partial discharge in power transformer

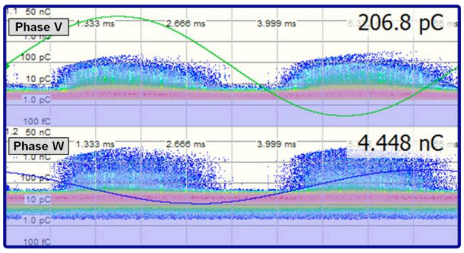


**Figure 8:** Electrical PD pattern recorded at the bushing taps of phases V and W

An example of the acoustically detected PD signals is shown in Figure 9. The signal shape on all sensors indicated propagation paths with just minor attenuation. The yellow sensor detects the signal first, shows no indication of an acoustical steel path and the highest signal amplitude. These facts indicate this sensor as being the one closest to the PD defect. The black sensor seems to have a short steel path while the sensors blue and red show an increasing signal shape which usually can be considered as an indication for signal damping due to crossed solid insulation. This overall behavior has been found as being reproducible and so a localization could be carried out. The signal speed used for the calculations was set to 1400 m/s and the start points of the signals were determined using the energy criterion and adjustment by hand in some cases. The resulting circles indicating the position of the PD source are automatically given by the location system PDL 650 and are to be seen in Figure 10. A brown dot marks the PD source at the intersection of the circles.

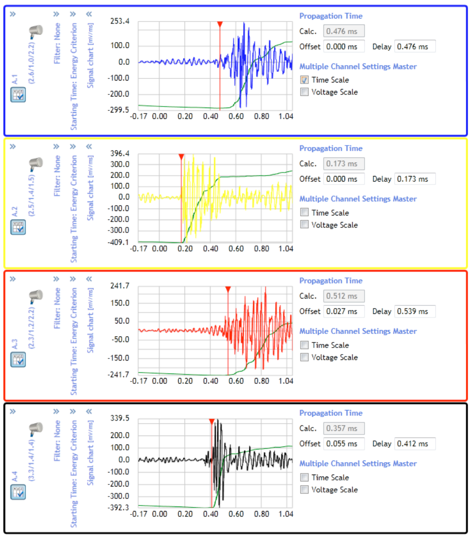


**Figure 9:** Acoustical PD signals detected during the location procedure

The subsequent inspection of the transformer verified a close match of the defect (Figure 11) and the estimated PD source.

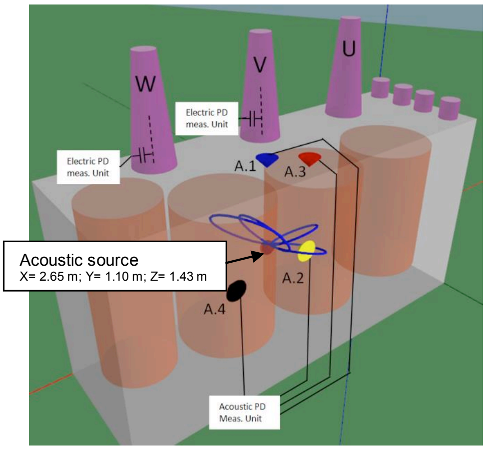


**Figure 10:** Computer model of the tested transformer, sensor positions and located PD source

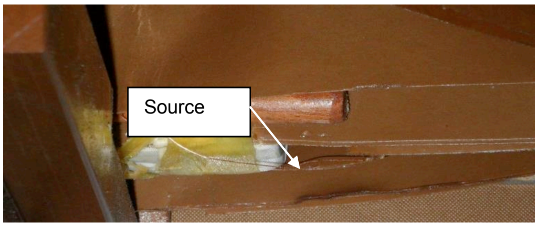


**Figure 11:** Finding: Bare Wire close to the main insulation found as root cause of PD activity

### 4.2 PD location on a 100 MVA transformer by using UHF signals as trigger source

The following investigation was performed on a 230 kV/20 kV three-phase power transformer (100 MVA) in a manufacturers test field. The UHF and conventional electrical PD measurement according IEC 60270 [1] revealed the quite comparable PD patterns shown in Figure 12. Both signals were potentially qualified for triggering the acoustical measurement system.

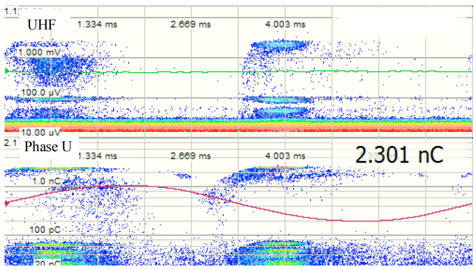


**Figure 12:** Simultaneously measured PD pattern of the UHF system (top) and conventional PD detector at the bushing tap

# Acoustic and electrical methods combined for localizing partial discharge in power transformer

The UHF measurement was performed by using the narrowband acquisition method with a bandwidth of 1.5 MHz. The center frequency of 159.5 MHz was chosen based on the evaluation of the frequency sweep shown in Figure 13. The highest signal energy of the UHF spectrum is shown as the upper line representing the pulses - including the PD - while the sinusoidal or continuous wave (CW) disturbances are shown in the lower curve. The measurement frequency can now be tuned into an area showing a large distance between both lines. This method turned out as being very effective to optimize the signal-to-noise ratio during a UHF PD measurement.

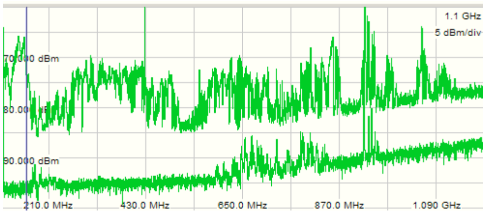


**Figure 13:** UHF Frequency sweep of the spectrum inside of the transformer and the measurement filter used shown as grey bar at 159.5 MHz

Figure 14 shows the 3D computer model of the transformer with the final sensor positions and the electric-acoustic test setup.

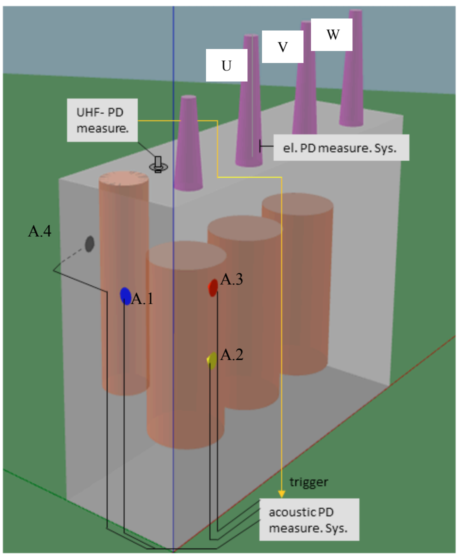


**Figure 14:** Test setup (UHF, el. and acoustic PD)

After optimizing the UHF signal quality the pulses detected by the UHF 620 system were used to trigger the acoustic PD localization. The evaluated time delay led to PD source positions on the outer surface of the tab winding between winding and tap changer as shown in Figure 15.

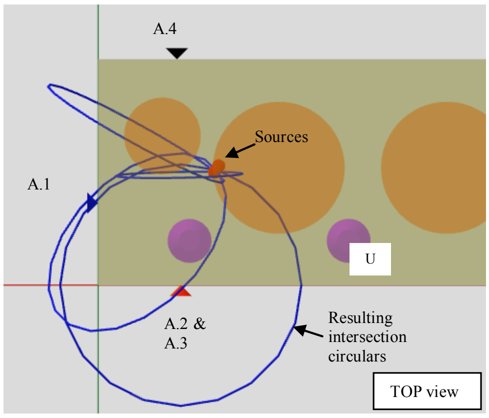


**Figure 15:** Estimated PD source location and some intersection circulars

The subsequent inspection of the transformer verified a close match of the defect and the estimated PD source.

### 4.3 PD location on a 500 MVA transformer in the field (all acoustic)

A 500 MVA unit showed significant increase of hydrogen and methane a few months after installation. Figure 16 shows the transformer and its modelling in the localization software.

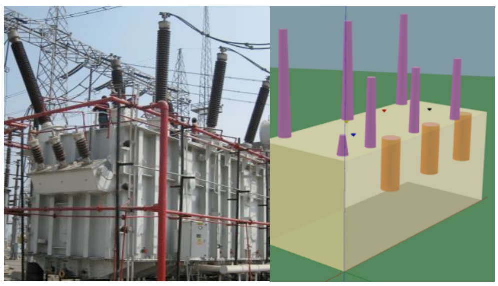

**Figure 16:** The unit under test and its representation in the localization software. Sensors are visible on the top.

In this case the internal structures shown are the tap changer compartments. During the initial PD location electrical triggering could not be utilized. Furthermore a detection of acoustic signals on the tank walls was not possible, presumably due to the magnetic shunts which are known to have a significant sound damping characteristic. Thus, the acoustic sensors had to be attached on top of the transformer. The results measured with the first sensor arrangement indicated a PD location at the middle phase, near the tap changer or the 220 kV bushing (see Figure 17, left). Therefore the sensors were re-positioned closer to the expected PD spot, what led to improved signal quality and higher sound levels. The resulting surfaces representing the mathematical solutions of the localizing equations can be seen on the right-hand side of Figure 17 and confirm the initial expectation about the PD location. The internal inspection of the tab changer connection via a man-hole discovered defects of different insulation elements which have been replaced. The transformer has been put back into service again and is in operation now without any indication of remaining PD problems.

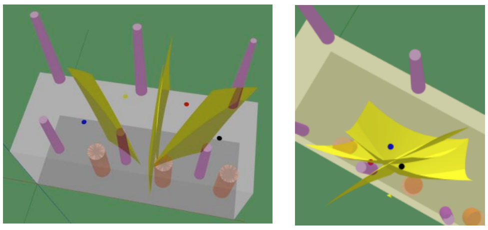

**Figure 17:** Results with initial sensor placement (left) and after sensor-repositioning (right). PD source indicated to be close to the tap changer or MV bushing of the middle phase.

## 5 CONCLUSIONS

This paper describes the basic idea of time based acoustical localization of PD faults in power transformers and similar equipment. The PD signals are captured using three or more piezoelectric acoustic sensors, magnetically mounted on the tank at different locations. For localizing the source, the time delays between the recorded acoustic signals or between an electrical signal and the acoustic signals are used to get information about the propagation of the acoustic signal inside the transformer tank and the distances between signal source and sensors. The received sensor signals are processed to obtain the difference between the signal arrival times at each sensor.

In addition to the acoustical measurement, a parallel electrical PD measurement can be used to obtain a trigger signal. This can be essential for the success of the localization. Alternative to the electrical measurement through the bushing taps or with external coupling capacitors, unconventional measurement techniques, e.g. in the UHF range, can be used to gain a trigger source for an acoustic measurement. Case studies of successful PD localization of a significant PD source have been shown. The procedure and successes of an acoustical measurement with electrical triggering has been shown. The results are analyzed and visualized by using a 3D model.

## 6 REFERENCES

[1] IEC 60270 (2000) „High-voltage test techniques - Partial discharge measurements" International Electrotechnical Commission, Publication 60270, 2000

[2] C57.127 (2007) "IEEE Guide for the Detection and Location of Acoustic Emissions from Partial Discharges in Oil-Immersed Power Transformers and Reactors", The Institute of Electrical and Electronics Engineers, Inc. New York, USA, 2007

[3] Howells, E. ; Norton, E.T.: "Parameters affecting the velocity of sound in transformer oil" IEEE Transactions on Power Apparatus and Systems (1984)

[4] Lundgaard, L.E. „Partial Discharge – Part XIV: Acoustic Partial Discharge Detection – Practical Application", IEEE El. Insulation Magazine Sep 1992 Vol.8,No.5

[5] Hoek, S.M.; Kästner, B; Kraetge, A; "Introduction to performing acoustic partial discharge measurements and localizations using the PDL 650" OMICRON electronics, Application Note ANP_12004_ENG, www.omicron.at (2013)

[6] Bengtsson, T.; Leijon, M.; Ming, L. "Acoustic Frequencies Emitted by Partial Discharges in Oil", 8th International Symposium on High Voltage Engineering, 1993, p.113-116

[7] Große, C.U.; Reinhardt, H.-W.; (1999) „Schallemissionsquellen automatisch lokalisieren" MP Materialprüfung, Jahrg. 41, pp.342, Carl Hanser Verlag, München, Germany, 1999

[8] Wagenaars, P.; Wouters, P.A.A.F.; van der Wielen, P.C.J.M.; Steennis, E. F. "Algorithms for Arrival Time Estimation of Partial Discharge Pulses in Cable Systems" IEEE Vancouver, Canada, 2008

[9] Coenen, S.; Tenbohlen, S.; Markalous, S.M.; Strehl, T. (2008) "Sensitivity of UHF PD Measurements in Power Transformers" IEEE Trans. on Dielectrics and Electrical Insulation, Vol. 15, No. 6, pp. 1553-1558

[10] Kraetge, A.; Rethmeier, K.; Hoek, S.M.; Krueger, M.; „Modern de-noising strategies for PD measurements on transformers under challenging on-site conditions", CIGRE SC A2&D1 Colloquium 2011, Kyoto, Japan, Paper # PS1-O-14