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ULTRASONIC METHOD FOR TESTING OF POWER TRANSFORMERS

SUMMARY

Ultrasonic method of detecting PD is based on the fact that the electrical energy of the PD transforms in a mechanical energy, an ultrasonic acoustic wave that spreads through the transformer to the tank wall. From time difference of wave detection on different sensors, a possible location of the source can be estimated. Ultrasonic method can detect other transformer deficiencies such as loose contacts and local overheating of oil (T>200°C).

Three case studies are given in this paper. The first case was where DGA indicates the thermal problem in the oil and the result of ultrasonic testing points at OLTC contacts. In the second case an ultrasonic method was performed after electrical method detected high levels of PD at voltages much lower than the nominal. Ultrasonic method detected non-grounded parts of the returning limb electrostatic screen. In the third case, a failure of transformer, namely a breakdown from the HV bushing end shield, initiated a series of tests on similar transformers installed at the same substation. The assumption was that PD occurred in the shied epoxy insulation and eventually caused the breakdown.

Key words: diagnostics, power transformer, partial discharges, ultrasound, acoustic emission

1. INTRODUCTION

Partial discharges (PD) in power transformers occur as a result of local dielectric overstress of insulation. PD in power transformers with oil-paper insulation result in electrical, chemical and acoustic effects. Their detection can be carried out with several techniques, according to the effects that they produce. Standard method in HV testing technique is an electrical method, which is a part of the quality control in a factory (standards IEC 60270:2000 [1] i 60076-3:2000 [2]). PD in a transformer produces gases, which are the result of a chemical degradation of oil and paper. This is a basis for Dissolved Gas Analysis (DGA) method that determines the amount of characteristic gasses dissolved in oil. Disadvantage of this method is that the PD source needs to be active for a relative long period, long enough to produce measurable levels of gas. Even thou this methods are useful, they only give information of the presence and/or magnitude of PD but not their location. Determination of location of the source is extremely important because the severity of the fault depends on the location of its origin. It is not necessary to accentuate that this is important for repair as well as where will it be performed, on site or in the factory. A possibility for on-site repair is always limited by the availability of the location, taking in consideration man holes on the transformer tank as well as the technical limitations, especially if there is a need for an extraction of the active part.

Short-term PD, even with high intensity often leaves no traces on the insulation, making a visual determination of the fault unlikely, even after the disassembly of the transformer. Application of electric method enables only rough approximation of the location (i.e. which phase) and determination of its

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character, but only in laboratory conditions. DGA has practically no possibility of location determination, except the determination is the fault mostly in oil or in oil impregnated paper.

However, the ultrasonic method imposes as a solution for location of the PD source. Ultrasonic method of detecting PD is based on the fact that the electrical energy of the PD transforms in a mechanical energy, an ultrasonic acoustic wave that spreads through the transformer to the tank wall. These waves are detected with piezzo-electric sensors, which transform this mechanical wave in to an electrical signal. From time difference of wave detection on different sensors, a possible location of the source can be estimated. Main difference of this method is that its main feature is location of the fault and secondary its detection.

Since the method detects ultrasonic acoustic waves spreading trough the tank it can detect other transformer deficiencies such as loose contacts and local overheating of oil (T>200°C) which gives this method an unique diagnostic status[3].

2. MEASURING METHOD

Standard measuring equipment consists of 24 resonant sensors and a computer acquisition and signal analysis system. Sensors are piezzo-electric type, with resonant frequency 150 kHz, shielded for the purpose of electromagnetic disturbance elimination. Band pass is between 70 and 200 kHz which makes them sensitive to PD, and less sensitive to external noises. Position of each sensor is inputted in a coordinate system along with the transformer dimensions. Placement of the sensors mostly depends on the construction of the transformer having in mind the most critical points of possible PD origins. After the sensors are placed and the system is adjusted calibration of the sensors is performed. Calibration is performed according to Hsu-Nielsen method which gives an approximately the same character of acoustic discharge as a PD [4].

Duration of the test depends on the intensity and repeatability of the acoustic signal. Therefore there are significant differences in the test duration depending on the test location, on-site or in the factory. The duration of the test on-site is usually 24 h in order to cover the entire day cycle of transformer burden. In test stations, acoustic activity can be provoked (either by raising the voltage or current) and therefore test time could be reduced.

At least four sensors should detect the same acoustic discharge to determine its location. If less than four sensors detect discharges, some of non active sensors should be moved to the area of acoustic activity. Of course, sensor dislocation prolongs the test time.

After the test is complete, analysis is performed. During the analysis noises are eliminated, activity with mechanical character is removed and the correlation of activity with respect to working parameters of transformer (voltage, burden, operations of OLTC, cooling system operation) is evaluated.

Conclusion of the possible fault location is given after the thorough analysis of the acquired data.

Possibility of locating PD in power transformers with respect to its origin is given in table I. As the distance between PD source and the tank increases and as the number of obstacles on the wave path increases, the possibility of detection and therefore location decreases.

Table I. Possibility of acoustic source localization [5]

Origin of acoustic wave	Detection	Note
Connections and leads	Yes	High possibility of location
Inner winding	Uncertain	Depends on the position of the winding
Between first winding and core	Unlikely	Very high damping
Between the core and the tank	Yes	Moderate possibility of location
Inside the bushing	Possible	If sensors are placed near the flange of the bushing
DETC	Yes	High possibility of location
OLTC	Yes	High possibility of location

Location calculations are based on a simple relation between time, distance and the speed of an acoustic wave according to (1).

$$d = v \cdot t \quad (1)$$

The majority of the calculation modes are a variation of 2 dimensional source location in a plane, although in many cases the 2D plane will wrap around a 3 dimensional object. For 2 points in a flat plane the distance is:

$$d = \sqrt{(x_2 - x_1)^2 + (y_2 - y_1)^2} \quad (2)$$

This calculation is complicated by the lack of knowledge of the exact time the event originated. To get around that problem, all the times are considered relative to the first hit in the event. Each arrival time differences imply a difference in distance to the sensor relative to the distance to the first hit sensor. For the second hit sensor relative to the first hit sensor, a difference equation can be written as:

$$t_2 - t_1 = (d_2 - d_1)/v \quad (3)$$

or:

$$t_2 - t_1 = \left(\sqrt{(x_2 - x_s)^2 + (y_2 - y_s)^2} - \sqrt{(x_1 - x_s)^2 + (y_1 - y_s)^2}\right)/v \quad (4)$$

This equation contains two unknowns and cannot be solved without the second equation for detection on a third sensor:

$$t_3 - t_1 = \left(\sqrt{(x_3 - x_s)^2 + (y_3 - y_s)^2} - \sqrt{(x_1 - x_s)^2 + (y_1 - y_s)^2}\right)/v \quad (5)$$

When a discharge is detected by multiple sensors, using a regression analysis, the system searches possible location that best fits all the available data. [6]. An example of location determination on a plane with 3 sensors is given on figure 1.

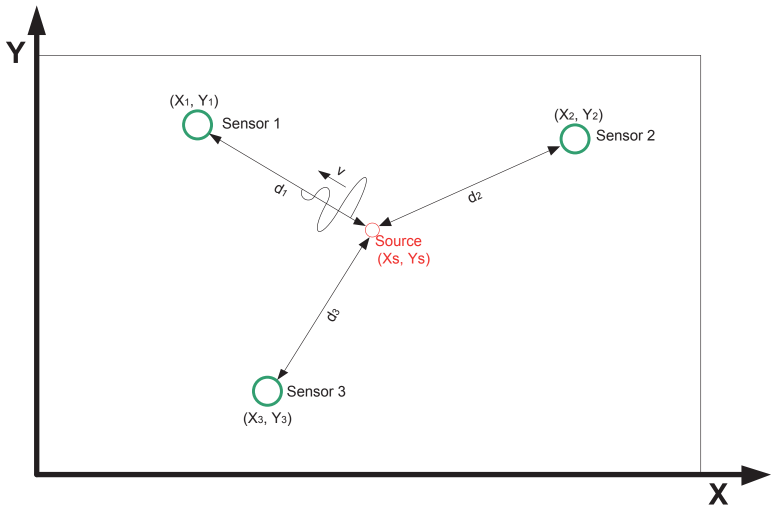


Figure 1. Determination of location on a plane

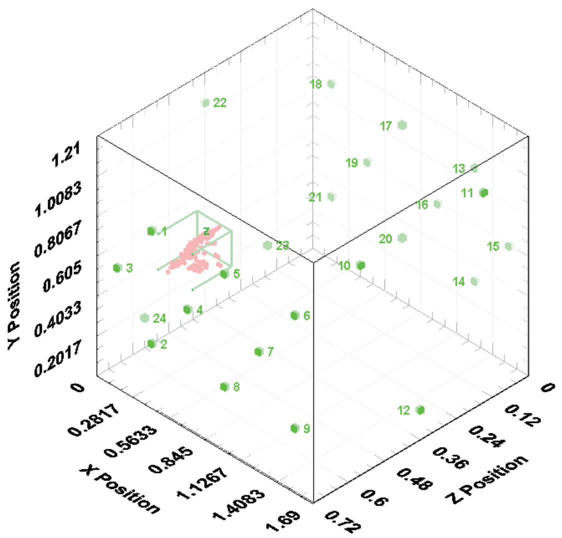
The lack of knowledge of the exact difference between time the event originated and the time when it was detected by the first sensor can be solved by the application of a Rogowski coil. A rogovski coil is a high frequency current transformer that is placed around the transformers earthing or neutral point lead. Since the propagation of an electric signal is almost instant, the Rogowski coil detects the time when the discharge originated. Therefore, another equation is added in calculation which enhances precision of the calculations.

Since the system detects acoustic emissions spreading trough the tank, the detected hits can originate not only from the actual fault but also from vibrations, external disturbance, reflections etc. In order to differentiate the origins of the signal, parameters of the recorded hits should be evaluated. For example, the system can display the amplitude, energy, duration, counts, frequency etc in respect with test time or relatively to each other. Since PD, local overheating and disturbances have different characteristics the mentioned capabilities are used during analysis.

Implementation of the method was performed in High Voltage laboratory of Končar-Electrical Engineering Institute. Source of PD (figure 2) was placed in a tank of a transformer model, 5 MVA, with dimensions 1,7x1,2x0,7 m. The measurement was performed with de-energized transformer, and the voltage was applied only to the PD source. Parallel to the acoustic method an electric method for PD measurement was used.

Figure 2. Sensor placement (left), PD source (right up) and its placement in the tank (right down).

With the level of 500 pC, system detected a possible location of PD (figure 3). The cluster with the highest density of detected locations is bounded in the green box. Green dots represent the locations of the sensor and the red dots detected locations. It is necessary to note that the dimensions of the axis are not in the same ratio (the system gives a 3D layout as a cube).



Dimension of location cluster:

X axis: 0,472 – 0,586 m
Y axis: 0,715 – 0,895 m
Z axis: 0,590 – 0,715 m

Figure 3. Cluster location at 500 pC

The actual location of the PD source was at: X= 0,530 m , Y= 0,810 m, Z= 0,690 m.

The deviation of the detected location from the actual location of the PD source is within ±0,1 m. The system was tested to determine the lowest PD level at which it gives a satisfactory precision. Sistem was tested at 100, 900, 700, 500, 70 and 50 pC. It was determined that the system stil shows a correct location of the source at 70 pC while at 50 pC the locations are more dispersed, but even then the system still detects the existence of PD. (Figure 4).

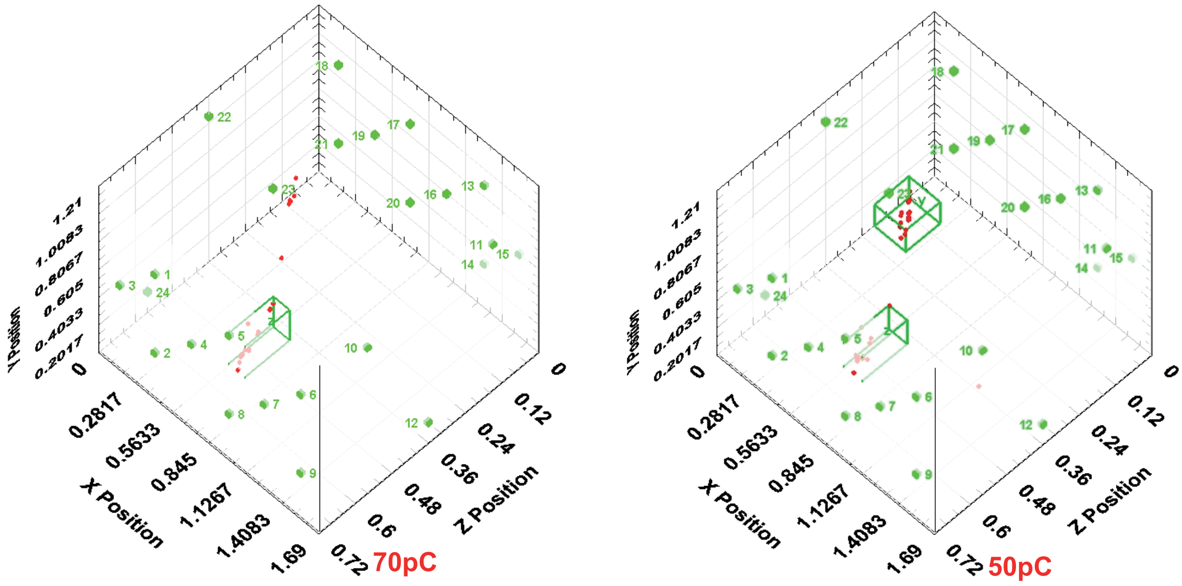


Figure 4. Location clusters at 70 and 50 pC

Even thou the method detects such small levels of PD, it is an artificially generated source with an de-energized transformer. On-site it is highly unlikely to detect discharges of such small level due to surrounding interference as well as interference from the transformer itself.

3. CASE STUDIES

3.1. Case1

Ultrasonic testing of transformer 200 MVA, 220/115 kV was initiated by high levels of dissolved gasses in oil, especially ethylene (2122 ppm) and methane (1007 ppm). High levels of these gases indicate a thermal fault, local overheating without the presence of paper.

Highest acoustic activity was recorded by sensors placed in the region of OLTC. Results, before and after analysis are showed on figure 5. During the analysis noises, reflections and mechanical interference was removed, as well as the disturbance originated from the atmospheric conditions (rain, wind etc.). After the analysis locations were obtained within the blue cluster.

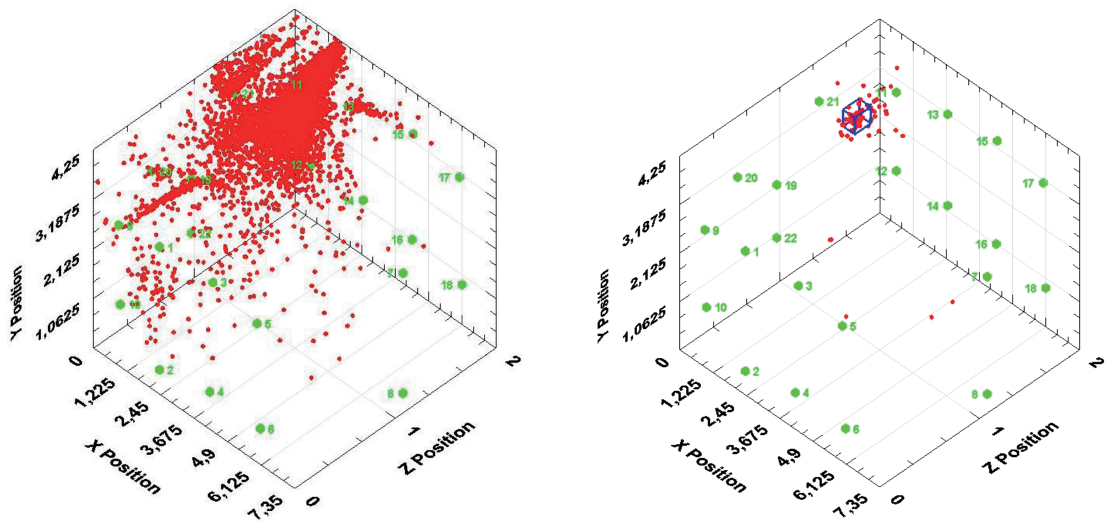


Figure 5. 3-D view of obtained locations before (left) and after the analysis (right)

Different views of the transformer are shown on figure 6 along with the sensor positions and obtained locations. OLTC position was added afterwards. Since the axes are not in the same scale OLTC has an oval shape instead of a circular.

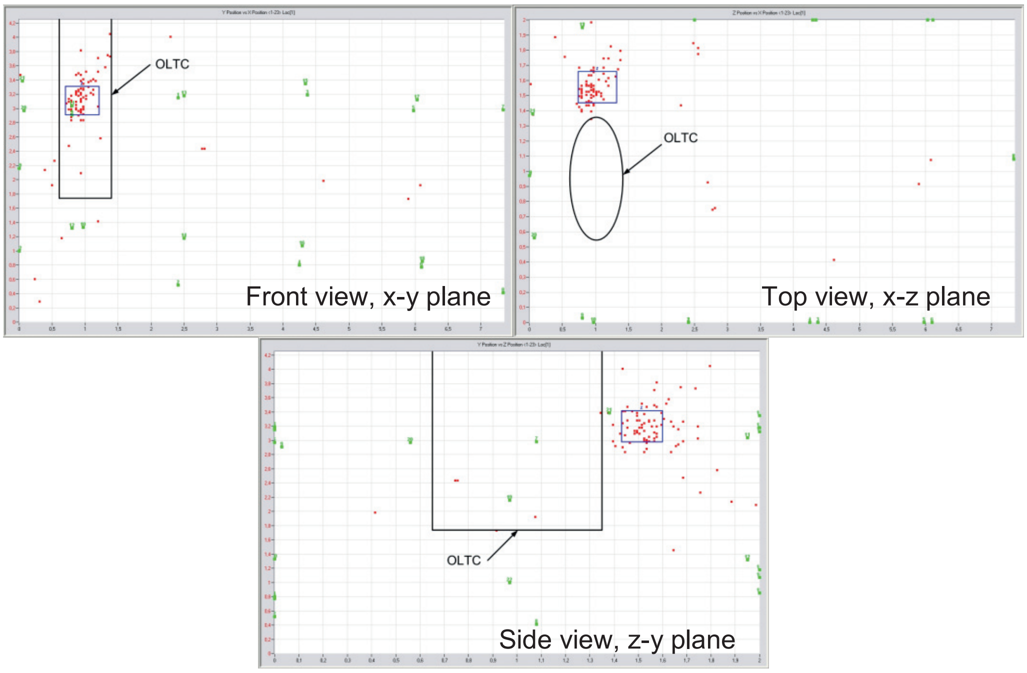


Figure 6. Obtained locations – front, top and side view

Obtained locations, a cluster of the highest density, points to a region where some of the contacts of OLTC are placed. Test result could indicate a bad connection between OLTC contacts and outputs of regulating winding. Na The most active part of the transformer is marked with a red square on figure 7.

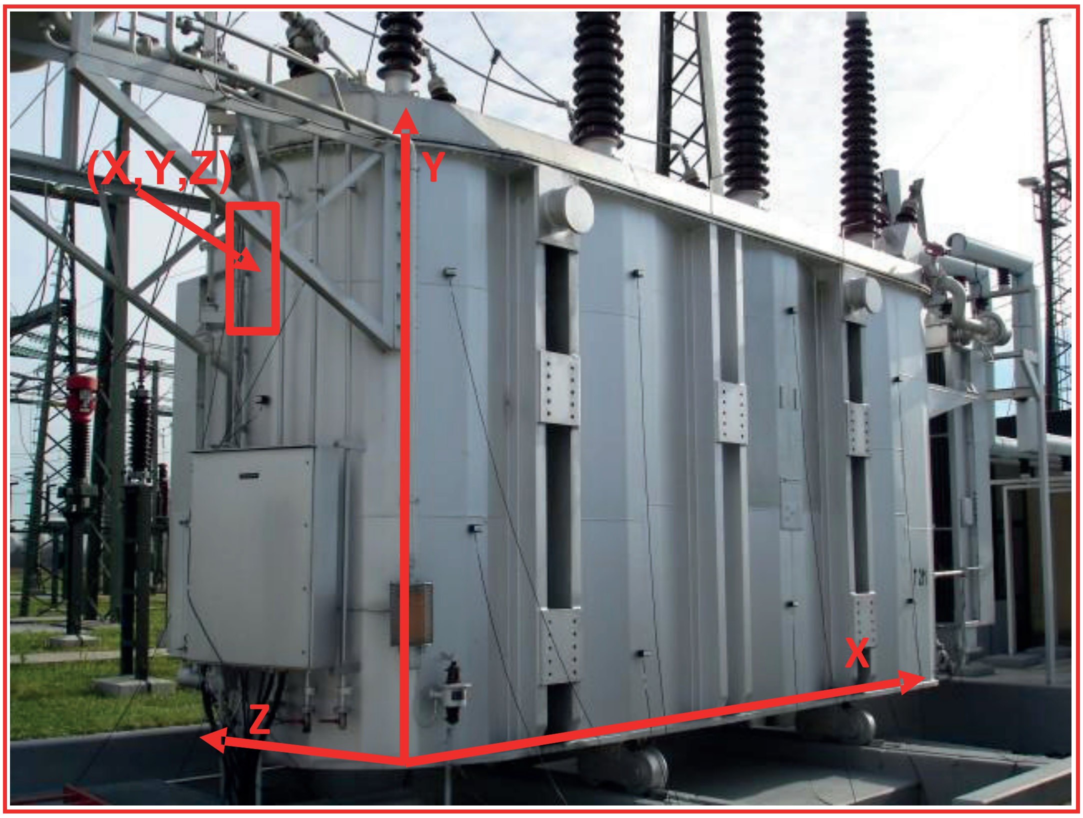


Figure 7. Area of highest activity

After the test it has been determined that there was a significant deviation of winding resistance measured in one of the OLTC positions. This position was not used and there was no further rise of dissolved gases.

3.2. Case 2

Ultrasound emission testing of a power transformer 400 MVA, 400/220 kV has been initiated because the electric method has detected partial discharges (in following text PD) during routine testing.

During the laboratory tests two independent areas of acoustic activities were obtained. Acoustic activity was recorded even at low voltages (switch on voltage). The positions of obtained locations (red dots) before the analysis are showed in figure 8. One area indicates an acoustic emission source in the region of phase 1U returning core limb (5 limb core), and another, an acoustic emission source in the region of 1W returning core limb.

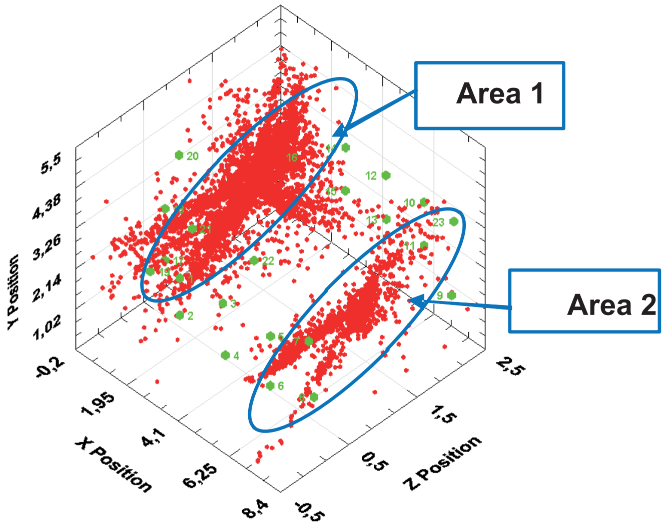


Figure 8. Obtained locations – 3D view – before analysis

After analysis, two clusters (green box on figure 9), were obtained (areas were analyzed separately).

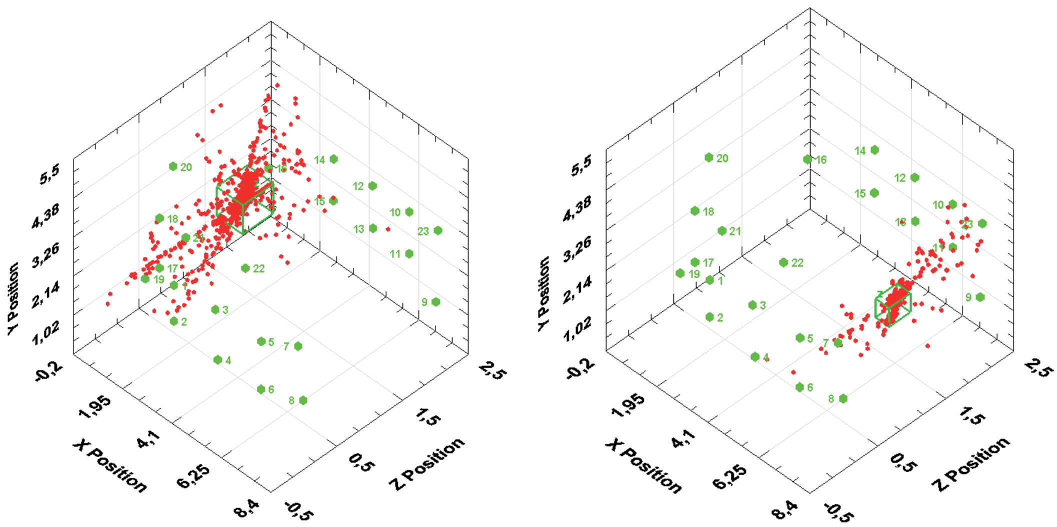


Figure 9. Obtained locations in region of returning core limb 1U (left) and 1W (right)

Areas of highest acoustic activity are shown on figure 10 (marked red). This result indicated that there are acoustic emission sources in the region of both returning core limbs.

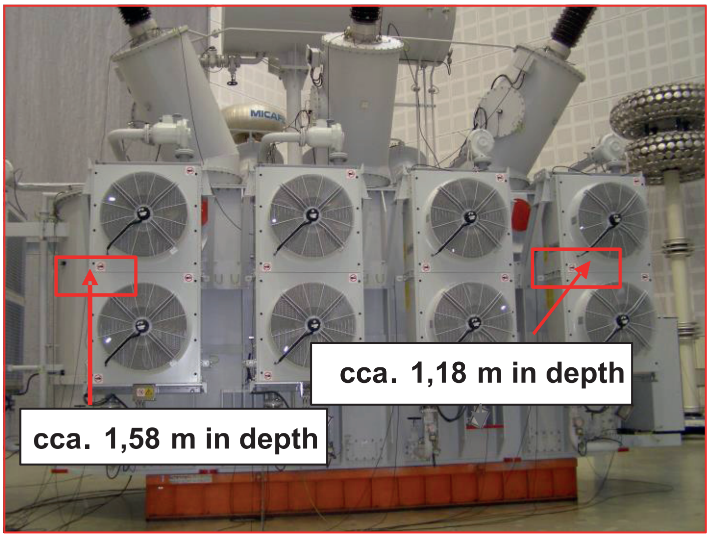


Figure 10. Areas of high acoustic activities (based on 3D clusters)

The transformer was opened and inspected. It was determined that a part of electrostatic screen of returning limb did not have defined potential, i. e. they were not properly grounded and produced sparking.

3.3. Case 3

Ultrasonic testing of bushing end shield was initiated by two breakdowns of a 400 kV in-service bushing in the region of end shield. Bushings were mounted on different transformers while the circumstances of breakdown were similar. Ultrasonic on-site testing was performed on 4 transformers with the same type of bushing and end shield, with major attention paid to the region of end shields. No significant acoustic activity was recorded. End shield consists of the screen electrode embedded in epoxy-resin so there was a possibility that acoustic activity of PD-s occurring in epoxy-resin insulation is heavily attenuated.

Therefore a laboratory test was initiated. A test setup was assembled to produce the same electric field strength as in-service (figure 11). Several end shields were tested using an electric method and ultrasonic method simultaneously.

Figure 11. Screen electrode test setup

Four sensors were placed at the bottom of the test tank. One of the end shields (screen 1, figure 12) showed high PD-s but with very low acoustic activity. This activity is within the range of surrounding noise of an on-site test.

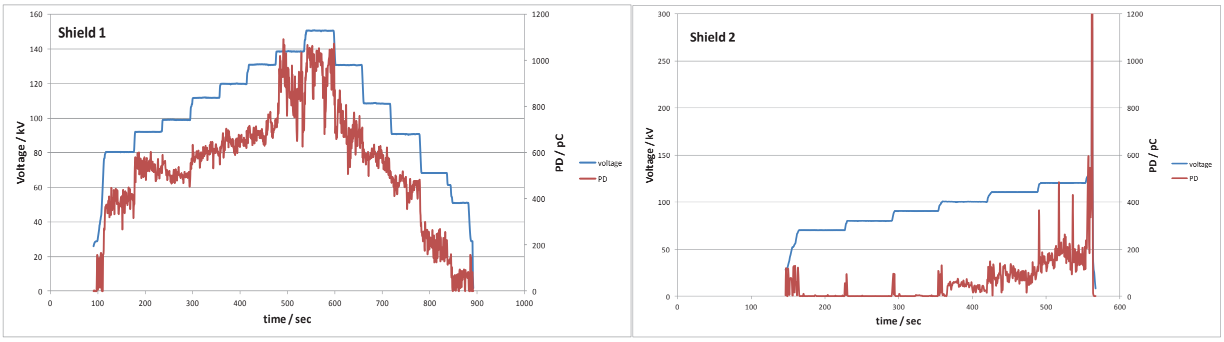


Figure 12. Plot of voltage and PD level vs. test time

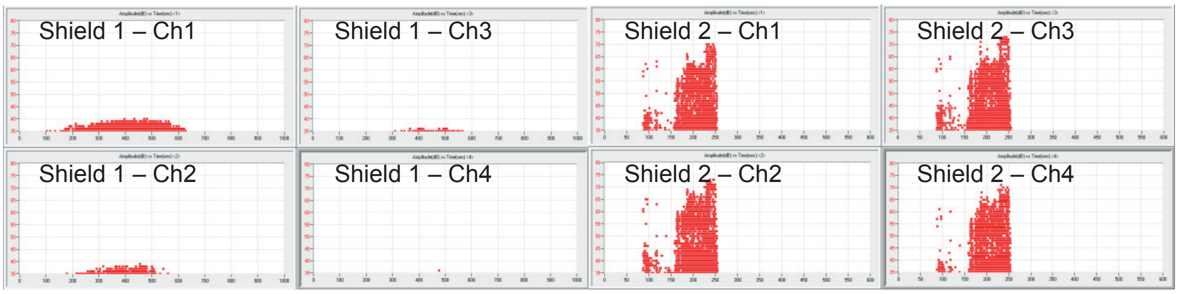


Figure 13. Plot of Acoustic activity vs. test time for both screens

As it is showed on figures 12 and 13, test of screen no. 1 showed very low acoustic activity even when PD levels were above 1000 pC.

To check the sensitivity of ultrasonic system in the existing test setup, a test of end shield no. 2 with damaged epoxy insulation (screen electrode in contact with oil) was performed. Ultrasonic system detected high acoustic activity even at PD levels lower than 10 pC. Since there was a risk of breakdown the ultrasonic system was shut off. Breakdown of shield 2 occurred at 130 kV.

Therefore it is very likely that the damping of acoustic waves generated in epoxy-resin insulation is too high and cannot be detected by the sensors placed on the tank of the transformer.

4. CONCLUSION

Partial discharges and hot spots with temperatures above 200 ^{o}C in oil impregnated insulation produce acoustic ultrasonic waves. This effect is a basis for ultrasonic testing of power transformers. Main task of this method is not detection, but to locate a possible defect inside the transformer. Entire preparation of the test and measurement can be performed during normal operation of transformer. This makes this method suitable for on-site testing, especially for important transformer, which, when switched off, can influence the stability of a power system. Besides that, a known location of the fault makes it possible to decide where the fault can be repaired, on-site or in the factory.

Possibility of locating PDs depends on the location of the fault inside the transformer. For instance, a fault on the OLTC, DECT, contacts, leads and any other part of the transformer that is located between the core and the tank is very likely to be located. Even PD-s inside the bushing can be detected in some cases. A fault inside the winding or in between the winding and the core is not likely to be detected due to high damping of an acoustic wave. As it is pointed in case study no. 3, PD inside the epoxy-resin insulation is unlikely to be detected. Laboratory test showed that acoustic activity within the epoxy-resin insulation with levels up to 1000 pC produce low acoustic activity in the range of a surrounding noise of an on-site test. Ultrasonic system detected PD levels only when they were higher than 300 pC. Therefore, a long lasting PD can damage the insulation of a screen electrode without a possibility of detection by means of any common method (DGA shows no rise of dissolved gases). This can lead to a breakdown without warning.

Ultrasonic method is recommended when one of the standard diagnostic methods or monitoring systems indicate a possible problem, i.e. when DGA shows high electrical or thermal stress inside the transformer. It is also applicable as a fingerprint on-site test in the early stages of transformer operations which can lead to a better diagnostic conclusion of an ultrasonic testing in the later stages of transformer operations. In a combination with other diagnostic methods (DGA, electric method of PD measurement) this method represents a step forward in power transformers diagnostics and can result in a significant savings in transformer maintenance.

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