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Power Transformer Diagnostics Based on Acoustic Emission Method

Wojciech Sikorski and Krzysztof Walczak

Additional information is available at the end of the chapter

1. Introduction

Partial discharge (PD) diagnostics is a proven method to assess the condition of a power transformer. Too high level of PD in a transformer may quickly degrade its insulation system and lead to damage. If PDs are detected and located quickly, then the transformer may be repaired or replaced, thus preventing power outages (Bartnikas, 2002; Gulski & Smitt, 2007).

Partial discharges in power transformers in service are most often detected with DGA (Dissolved Gas Analysis) and afterwards located using acoustic emission method (AE) (Duval, 2008; Lundgaard, 1992; Bengtsson & Jönsson, 1997).

In regard to the possibility of location of defects generating partial discharges, acoustic emission is an important diagnostic method of power transformers and other HV equipment.

Widely applied techniques for the fault location based on AE method are: (i) measurement of the time difference of arrival (TDOA) of the acoustic signals, (ii) measurement of the acoustic signal amplitude in different areas of a transformer tank (standard auscultatory technique, SAT), (iii) advanced auscultatory technique (AAT), (iv) estimation of the direction of arrival (DOA) of the acoustic signal based on the phased-array signal processing (Markalous et al., 2008; Tenbohlen et al., 2010; Qing et al., 2010).

More and more frequent breakdowns of large power transformers, often ending with fire difficult to put out, compel to more critical evaluation of traditional diagnostics techniques based mostly on periodic testing. Ageing of network infrastructure causes that the possibility of insulation system damage resulting from defect developing in short period is becoming more and more real. This fact favours different kinds of monitoring systems, which, through continuous investigation of the most important transformer parameters, allow to early detection of coming damage.

While analysing described in the literature cases of damage of power transformers, one can observe that many of them were related to accelerated degradation of insulation system, caused by high activity of different kinds of partial discharges (Höhlein et al., 2003; Lundgaard, 2000). Therefore the PD intensity monitoring as well as monitoring of its dynamics changes in time, in selected, neuralgic points of transformer seem to be a very important indicator informing on coming damage.

Currently there are only a few commercial systems for partial discharge monitoring in the power transformer in the world. These systems are based on the method of measuring AE (*Acoustic Emission*) or UHF (*Ultra High Frequency*) signal and offer limited capabilities (Markalous et al., 2003; Rutgers et al., 2003). A drawback of these systems is that as autonomous devices they do not cooperate with superior systems, and only transmit information or alerts about the status of the unit, what makes difficult a subsequent analysis of the causes of failure and looking for correlation with other parameters recorded by the monitoring system of the transformer.

Project assumptions of the partial discharge online monitoring system, developed at the Institute of Electric Power Engineering of Poznan University of Technology, were quite different. The system was, of course, so designed and constructed that it can work as a standalone device, what corresponds to the demand on emergency short-term monitoring (e.g. by day or a few days). However, the authors designing device have made all effort to ensure that it can be also integrated with any system of full monitoring of the transformer, such as e.g. Mikronika SYNDIS ES, which has already been installed on tens transformers in the European transmission networks. Through open collaboration of systems, the data collected by the PD monitoring system are visible in the superior system, so that it is possible to perform a full correlation analysis with other recorded parameters (load, voltage, oil temperature, OLTC operations etc.). The first prototype implementation of the integrated system for PD monitoring and SYNDIS ES was performed on one of the power substations. Currently the authors have already got the annual experience related to the work of the system, what will be discussed later in the chapter.

2. Superior power transformers monitoring system — *Mikronika SYNDIS ES*

In the power transformer monitoring Mikronika SYNDIS ES system, which has been installed on a few substations, the functionality of the expert system was acquired due to implementation of the knowledge base consisting of mathematical functions and models of phenomena occurring in a power transformer. Basing on logical operations and implemented inference rules, the expert functions generate (in online mode) summary alarms, emergency signals and prompts for substation staff. Expert functions assign specific logical value to the rules and relations contained in the knowledge base. On their basis, the transformer condition is defined as *Normal*, *Warning*, *Alarm* or *Emergency*. The simulating calculations conducted in real-time are significant elements of evaluation of power transformer condition. Therefore, the specialized mathematical model of thermal state was elaborated basing on the elementary relations presented in the *IEC 60076-7 – Part 7: Loading guide for oil-immersed power transformers*. The

model includes relation between load losses and the temperature mean of the separate bushing and tap changer position. The model was expanded on the work of the three power transformer coils as well as the relation between cooling effectiveness and number of working coolers or radiator batteries was included in the model. Basing on simulations, possibilities of a power transformer load at the current surroundings temperature are calculated every minute. In order to efficiently manage the resources, besides load and temperature analysis one can distinguish the following thematic groups in the monitoring system:

- moisture content in oil,

- dissolved gas analysis,

- cooling system,

- on-load tap changer,

- bushings,

- partial discharges.

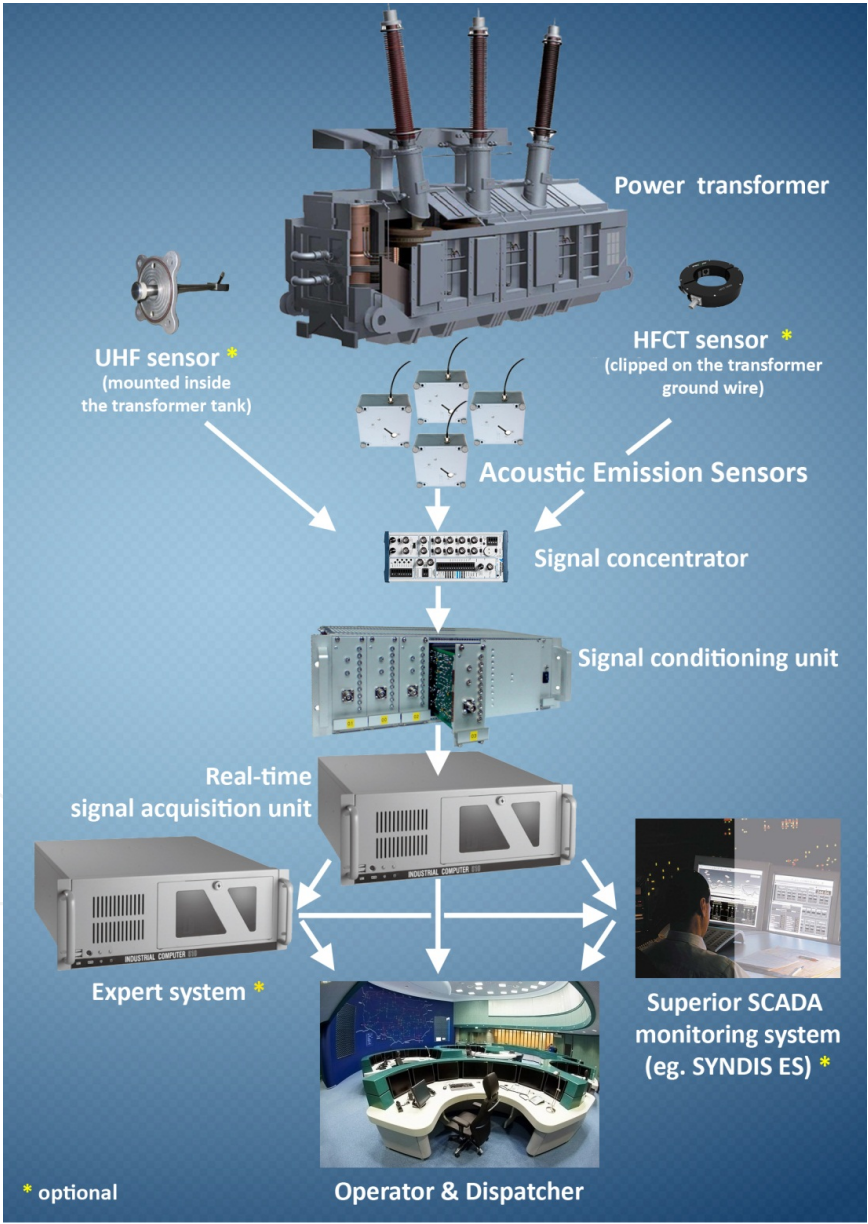## 3. Partial discharge online monitoring system

The prototype system for partial discharge monitoring presented in this chapter is the effect of several years of research, the results of which have already been presented, among others in (Sikorski & Walczak, 2010; Sikorski, 2012). In the mentioned literature items one can find more information on project assumptions and criteria for the selection of individual compo‐ nents of the system.

The system works basing on the detection of acoustic emission pulses recorded by piezoelectric contact sensors (PAC WD), which are mounted on the transformer tank. A practical solution enabling easy mounting of AE sensor with a constant force to the tank is the use of special handles fitted with strong permanent magnets and such solution was used in the prototype. The pream‐ plifier is also mounted in the handle. The amplifier and filters are located in standard 19-inch, fully screened industrial housing. From the conditioning module signals are transmitted to the acquisition module. Its integral element is a powerful workstation, based on multi-core architec‐ ture, with specialized software and ultrafast acquisition card installed. Procedures for the acquisition and analysis of data are implemented in National Instrument *LabView* program‐ ming environment and realized in real time. Acquisition module, like conditioning module, was placed in a separate screened industrial housing, compatible with mechanics standard 19-inch. The housing is waterproof and equipped with automatic temperature control system.

The system is designed for continuous, multi-month fieldwork, therefore specialized software allows not only for continuous registration of partial discharge activity, but also for correctness of the work of the system itself (e.g. temperature and humidity inside the enclosure or operation of electronic measuring circuits). The program is equipped with advanced data processing modules, which make it easier to evaluate events and noise filtering. In addition to

the registration and calculation of basic PD parameters (like the number of pulses, their energy and amplitude), the program creates also event log, whose goal is to inform, with a specified frequency (service station or the superior system), about the work of the PD monitoring system or threat to the transformer resulting from the intensity discharge growth. External communication is provided using a GSM modem (with an additional antenna) or LAN/WLAN network. The second solution was used in case of cooperation with the superior system of transformer monitoring SYNDIS ES.

The schematic diagram of developed partial discharge on-line monitoring system, which was in detail described in (Sikorski & Walczak, 2010), was presented in figure 1.

Figure 1. Schematic diagram of developed partial discharge on-line monitoring system

4. Partial discharge location techniques in power transformer

4.1. Standard and advanced auscultatory technique

Standard auscultatory technique (SAT) is one of the simplest methods of PD location. It involves the AE amplitude measurement in different areas of a transformer tank and thereby in different distance from the PD source. The SAT allows finding an area on a tank, in which the pulses of the highest amplitude/energy are recorded. One may assume that in this location under the surface of the tank, some depth in the object, the source of partial discharges' source is located.

The main advantages of the method are: (i) the possibility to carry out the measurements with one sensor, (ii) straightforward measurement procedure, (iii) the possibility of detection of the multi-source discharges, the occurrence of which in old transformers with aged insulation system is very probable (Sikorski et al., 2007, 2008, 2010).

Unfortunately, while employing the SAT method, very often one may expect errors in location of PD sources. This is because the amplitude of AE signal depends not only on the distance of a piezoelectric sensor from the discharge source (which is the basis of this measuring technique), but also depends on the energy fluctuations of partial discharges. Therefore satisfactory accuracy in the PD location with the SAT technique can be obtained only when discharges are stable (not self-extinguishing) and their energy does not change in time for the duration of the measurement. But taking into consideration that PD is a non-linear, dynamic phenomenon and has strongly stochastic character, this ideal situation is not very probable during the lengthy measurements performed on a real high voltage power transformer. The influence of small fluctuations of the PD energy on accuracy of discharges location with the use of standard auscultatory technique can easily be mitigated when one may determine the value of simple moving average (SMA) of the registered AE pulses' energy, e, and monitor the value of their standard deviation, σ. In case of fluctuations of the PD pulses' energy (e.g. their apparent charge q changes in a wide range, from hundreds pC to some nC), the procedure of AE-pulses energy averaging, does not give satisfactory results. The largest errors of the PD source location while employing the SAT method occur when the partial discharge activity is not-stable and after the period of high intensity we observe their extinction for a certain time.

In order to improve the efficiency and reliability of auscultatory technique, the authors propose to simultaneously monitor in each measuring point on the surface of a transformer tank the simple moving average of: (i) AE waveforms energy, $SMA(e)$, and (ii) the PD apparent charge, $SMA(q)$. Additionally, the parameter p is introduced that is equal to the quotient of the measured values $SMA(e)$ end $SMA(q)$. Due to this operation, the corrected value of the AE pulses energy depends mostly on the acoustic waves' attenuation effect, and so depends on the distance between a piezoelectric sensor and the PD source. The influence of the changes of PD energy on the result of the PD source location is then negligible.

The proposed algorithm of the AAT method consists of the following steps:

Step 1. Using the conventional electric method, identify the transformer phase, in which the partial discharges occur.

Step 2. On the transformer tank mark a grid of the measurement points, consisting of *m*-rows and *n*-columns (see Figure 2).

Step 3. For the given measurement point *a(i,j)*, where *i=1,…,m* and *j=1,…,n*, simultaneously register *r*-values of partial discharge apparent charge *q=(q₁,q₂,…,qᵣ)* and *s* AE-waveforms X=[*x₁,x₂,…,xₛ*].

Step 4. For the registered AE waveforms [*x₁,x₂,…,xₛ*] calculate their signal energy *e=(e₁,e₂,…,eₛ)*.

Step 5. For the registered values of the apparent charge *(q₁,q₂,…,qᵣ)* and the calculated AE waveforms energy *(e₁,e₂,…,eₛ)* determine their simple moving average (SMA): *SMA(q)* and *SMA(e)*.

Step 6. Calculate standard deviation *σ* of *SMA(e)*.

Step 7. If *σ ≤ 0.1* stop the acquisition, else repeat steps 3 through 6.

Step 8. Calculate the value of parameter *p*, which takes into account the influence of PD energy fluctuations on the energy of registered AE pulses in time for the duration of the measurements.

$$p = \frac{SMA(e)}{SMA(q)} \tag{1}$$

Step 9. Repeat steps 3 through 8 for all measurement points.

Step 10. Create matrix $P=[p_{i,j}]$.

Step 11. Create matrix $P_{norm}=[p_{normi,j}]$, which constitutes normalized values of matrix P in the range [0;1]:

$$p_{norm_{i,j}} = \frac{(p_{i,j} - p_{min})}{(p_{max} - p_{min})} \tag{2}$$

Step 12. On the base of the P_{norm} and the bilinear interpolation function generate a high resolution intensity graph (called *Acoustic Emission Map*).

Step 13. Superimpose the *Acoustic Emission Map* image on the photograph or construction drawing of the investigated transformer's phase, to find on the tank the areas which are the closest to the PD source.

Because the *Acoustic Emission Map* shows the result of PD source location on the 2D plane (see Fig. 3), it is recommended, if possible, to perform the additional measurements with the TDOA triangulation technique, by placing the AE sensors on the tank wall close to the area of highest *p* values localized with AAT.
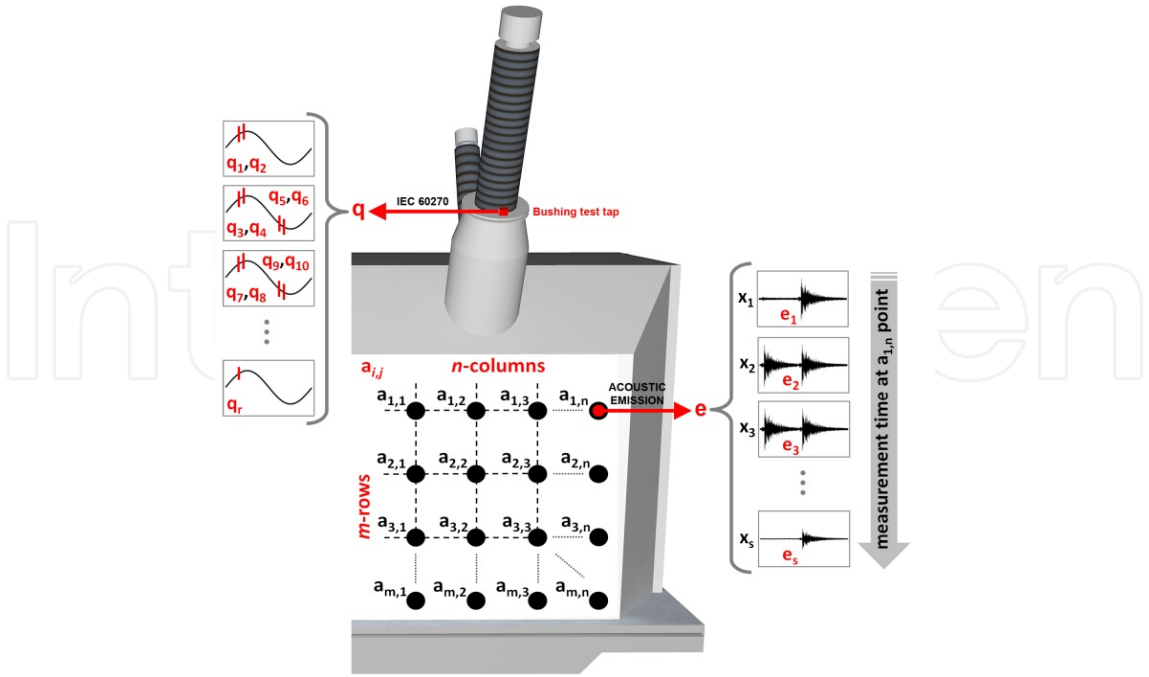
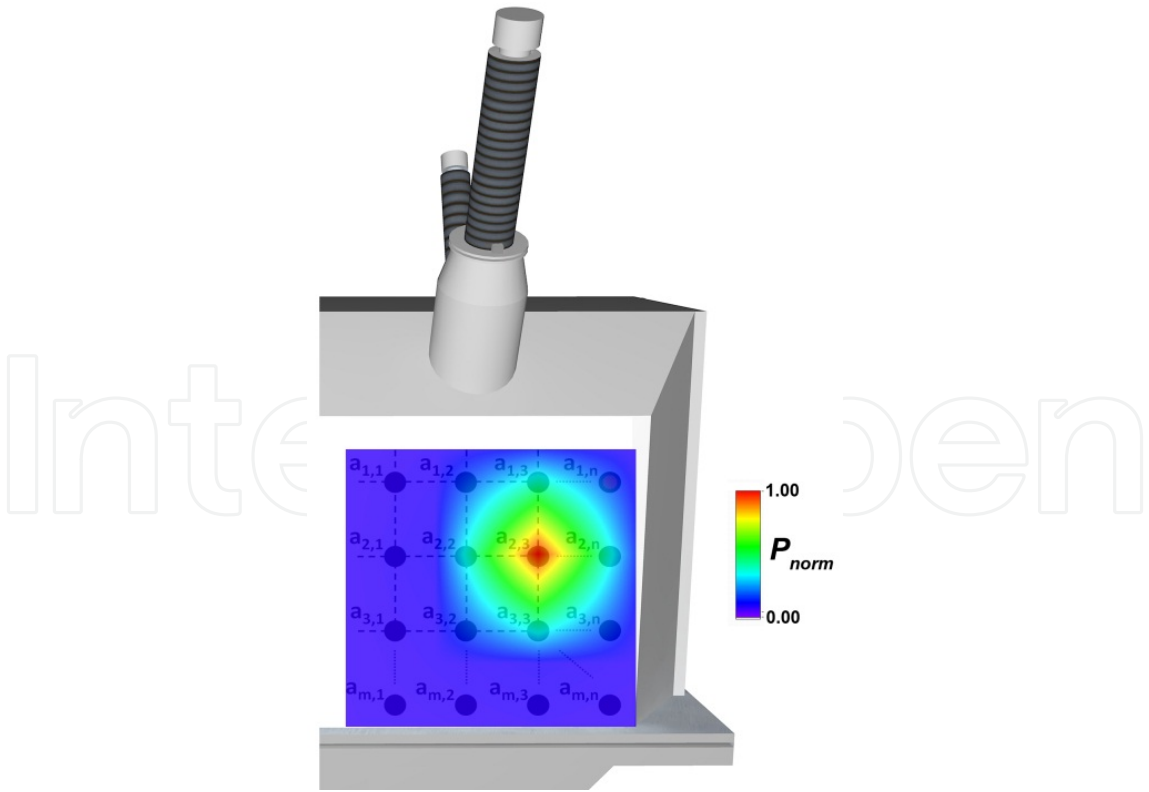**Figure 2.** Schematic diagram of AAT measurement procedure

Figure 3. Two-dimensional visualization (*Acoustic Emission Map*) of PD-source location results in advanced auscultatory technique (AAT).

The most important modification, comparing to the SAT method, is application of the parameter *p* which, to a very significant degree, minimizes the negative influence of the temporal changes of PD energy on the defect location results. This positive feature is illustrated by a simulation shown in figure 4. For simplification, it was assumed that the defect is present in the 'B' phase of the transformer, and the AE pulses were registered only in 7 measuring points. In the first case, it was assumed that the partial discharges are stable and their energy does not change in time for the duration of the measurements. Of course, with such an idealistic and almost unrealistic assumption, both techniques achieve identical and correct result of the defect location (Fig. 4a). As for the second analysed case, when energy of PD varies (fluctuate) during the acoustic emission signals' measurements, only the AAT technique allows to obtain the proper location of the defect (Fig. 4b).

The on-site PD measurement using a standard IEC-60270 PD detector is complicated. There-fore, the new AAT method is dedicated mainly for the transformer manufacturing plants and the repair companies. However, modern PD-detectors with the integrated noise-gating channel for noise-suppression via an external antenna and the software for noise reduction and filtering may also expand the AAT usage to transformers installed at substation (Kraetge et al., 2010).
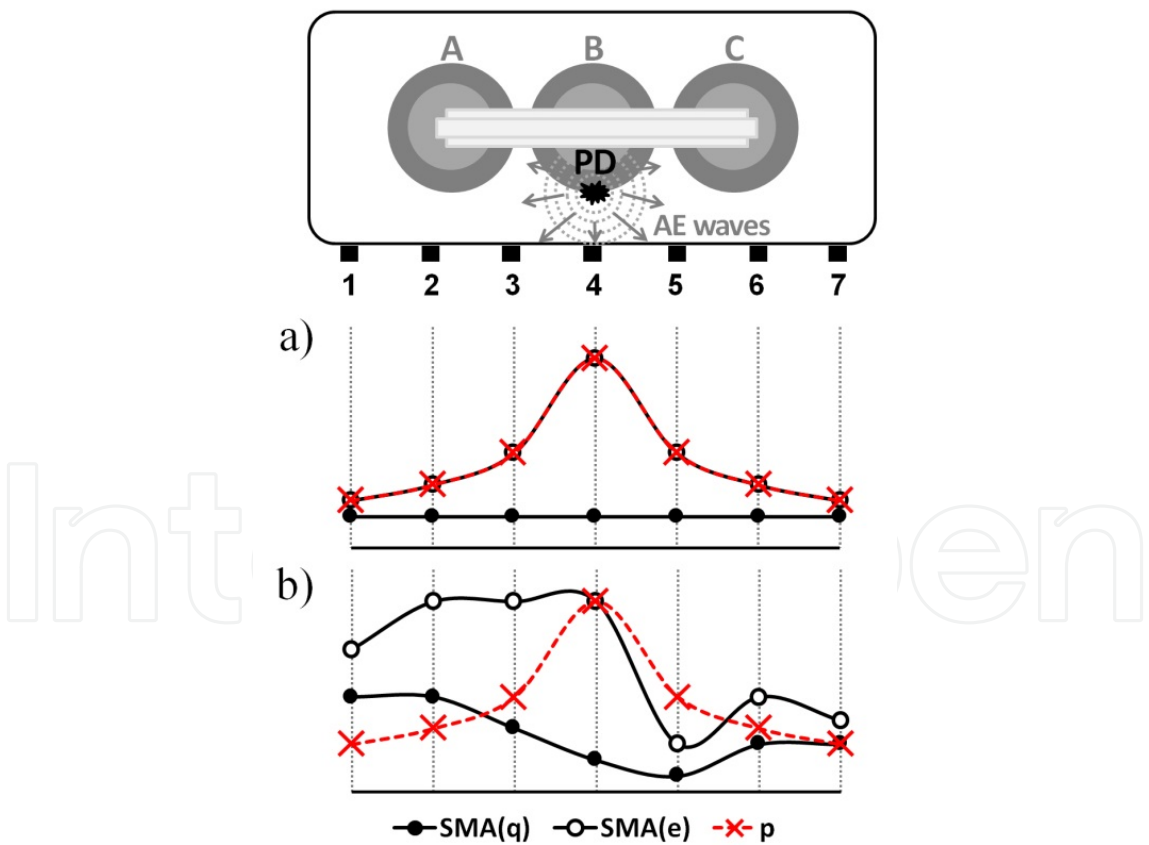
Figure 4. The diagram illustrating the result of PD location employing the parameter SMA(e) (standard auscultatory technique) and parameter p (advanced auscultatory technique) in case when the apparent charge of partial discharges is is: a) stable, and b) varying in time during the measurement.

Due to a low sensitivity of the PD detection procedure using acoustic emission method, the AAT method is the best for location of the defects that are the source of discharges with high energy (e.g. surface and creeping discharges, sparks), or defects that are close to a transformer tank (e.g. discharges in bushing and near the winding at the bushing connection, on the surface of outer pressboard barriers and spacers, etc.). Unfortunately, location of the internal PD sources (e.g. within the winding), is very difficult or even impossible. It concerns not only the use of AAT method, but any other technique that is based on acoustic emission.

Furthermore, it should be stressed, that complex and non-homogeneous internal construction of the transformer (pressboard barriers, supporting beams made of wood or phenolic resin etc.) and transformer tank (corrugated walls, magnetic or non-magnetic shields, stiffeners, gussets or ribs reinforcing the mechanical strength, welds etc.) impedes a proper interpretation of the AAT results because it causes a strong suppression of the acoustic signal.

4.2. Time Difference of Arrival (TDOA) technique

The PD source location based on TDOA technique is usually applied during on-site diagnostic tests of large power transformers. At least four AE sensors are used for spatial location of a defect $PD(x, y, z)$ in transformer tank. The sensors theoretically are fixed in different distances from the PD source (Fig. 5). The position of the defect is estimated basing on measured time difference of arrival of acoustic signals. In order to find the coordinates of defect one should solve the following nonlinear system of equations:

$$(x - x_{s1})^2 + (y - y_{s1})^2 + (z - z_{s1})^2 = (v_{oil} \bullet T)^2 \tag{3}$$

$$(x - x_{s2})^2 + (y - y_{s2})^2 + (z - z_{s2})^2 = (v_{oil} \bullet (T + t_{12}))^2 \tag{4}$$

$$(x - x_{s3})^2 + (y - y_{s3})^2 + (z - z_{s3})^2 = (v_{oil} \bullet (T + t_{13}))^2 \tag{5}$$

$$(x - x_{s4})^2 + (y - y_{s4})^2 + (z - z_{s4})^2 = (v_{oil} \bullet (T + t_{14}))^2 \tag{6}$$

where: x, y, z – unknown PD-source coordinates in space, T – unknown acoustic wave propagation time from PD-source to the nearest sensor numbered as S1, $x_{S1..4}$, $y_{S1...4}$, $z_{S1...4}$ - Cartesian coordinates of the four AE sensors S1...S4, t_{12}, t_{13}, t_{14} - propagation time delay between the sensor 1 and the sensors 2, 3 and 4 respectively ($t_{12} < t_{13} < t_{14}$), v_{oil} – acoustic wave propagation velocity in transformer oil (1413 m/s at 20ºC, 1300 m/s at 50ºC, 1200 m/s at 80ºC).

This nonlinear system of equations can be solved with one of direct (non-iterative) solver algorithms or with a least square iterative algorithm, which efficiency strongly depends on initial values selected by user.

The most common errors in accurate location of PD source coordinates using TDOA technique in large power transformers result from:

- simplifying assumption that the acoustic wave propagates only in oil with the velocity v_{oil} < 1500 m/s. This ignores the fact that acoustic wave propagates in transformer tank wall with velocity 5100 m/s as well.

- incorrect time-of-arrival estimation of signal propagating along the shortest geometric path. In regard to the fact that the velocity in metal is greater than in oil, the acoustic wave, which most of its way travels in tank wall (structure-borne path), arrives at the sensor first. Afterwards the sensor registers the wave, which propagated in oil slowly (direct acoustic path).

- inaccurate measurement of coordinates of the AE sensors as a result of complex transformer tank structure.
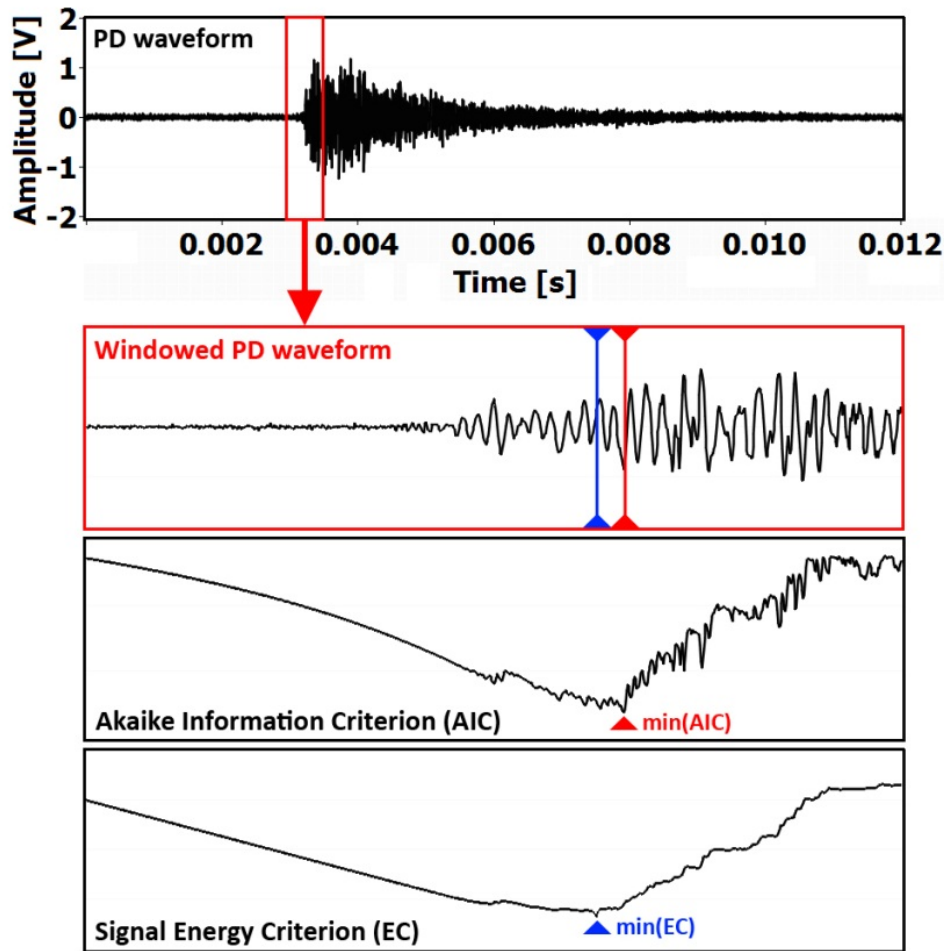
Time-of-arrival of partial discharge pulses is usually estimated by an experienced expert. It is also possible to apply an algorithm dedicated for automatic time-of-arrival estimation (so-called auto-picker). Currently used algorithms giving satisfying results base on the following criteria: (i) Signal Energy (EC), (ii) Akaike Information Criterion (AIC), (iii) Discrete Wavelet Decomposition (DWT), (iv) Gabor centroid, (v) Maximum Likelihood (ML), (vi) Phase in frequency domain and (vii) trigger level.
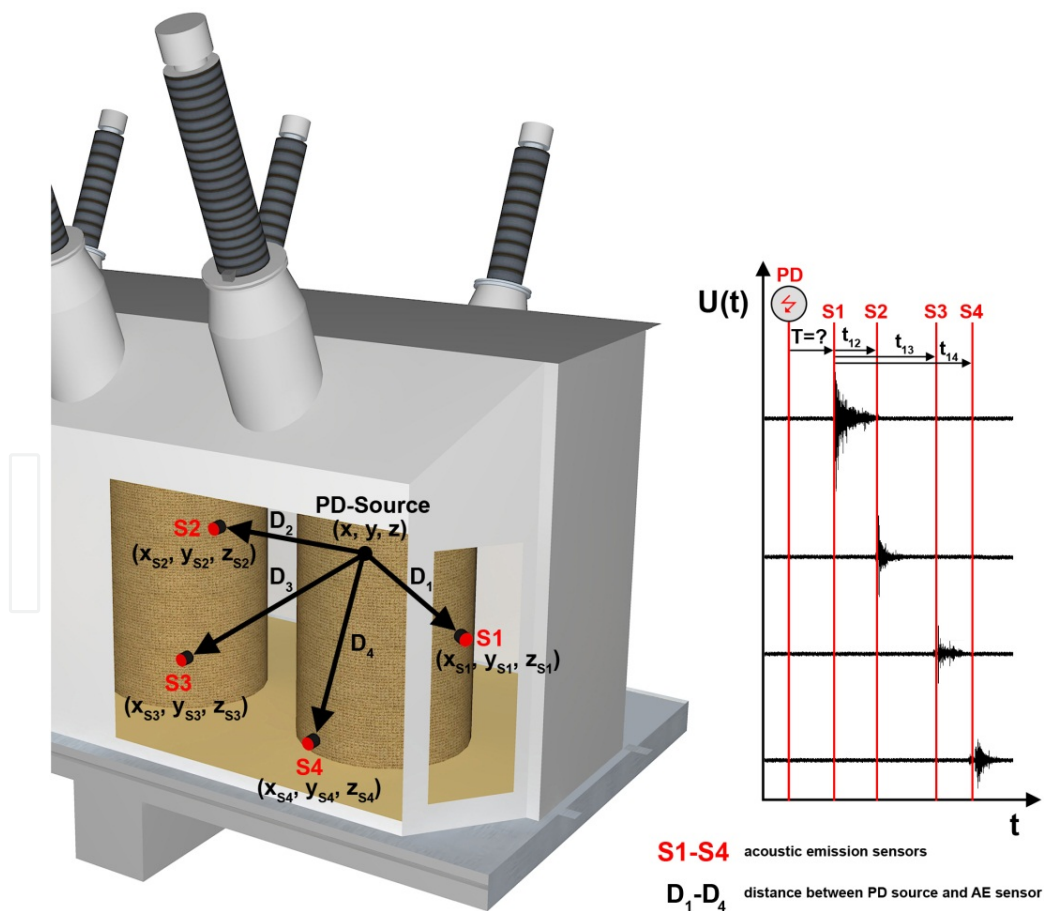
Figure 5. Schematic diagram of Time Difference of Arrival (TDOA) technique for partial discharge location in power transformer

In most cases, when signal-to-noise ratio (SNR) is high, the auto-pickers allow to estimate time-of-arrival with satisfying accuracy. In the rest of cases, it is necessary to apply additional advanced signal denoising methods, which increase the SNR.

The figure 6 presents the example of the time-of-arrival estimation of partial discharge pulse based on AIC and energy criterion.

Figure 6. Exemplary estimation of the time-of-arrival of partial discharge pulse based on AIC and energy criterion

The application of triggering with an electrical (IEC-60270 detector, only in laboratory conditions) or an electromagnetic (RFCT or UHF sensors, both in laboratory and on-site conditions) partial discharge signal is another variant of defects location technique (Fig. 7). The main advantages of simultaneous use of electrical/electromagnetic triggering and acoustic emission method are: (i) obtaining information on time of partial discharge initiation and (ii) reduction in the number of AE sensors required for measurement procedure (three are sufficient). In order to locate PD-source the following system of equations should be solved:

$$(x - x_{s1})^2 + (y - y_{s1})^2 + (z - z_{s1})^2 = (v_{oil} \bullet t_1)^2 \tag{7}$$

$$(x - x_{s1})^2 + (y - y_{s1})^2 + (z - z_{s1})^2 = (v_{oil} \bullet t_2)^2 \qquad (8)$$

$$(x - x_{s1})^2 + (y - y_{s1})^2 + (z - z_{s1})^2 = (v_{oil} \bullet t_3)^2 \qquad (9)$$

where: x, y, z – unknown PD-source coordinates in space, $x_{S1..3}$, $y_{S1..3}$, $z_{S1...3}$ - Cartesian coordinates of the sensors S1...S3, t_1, t_2, t_3 – measured absolute arrival times, v_{oil} – acoustic wave propagation velocity in transformer oil.
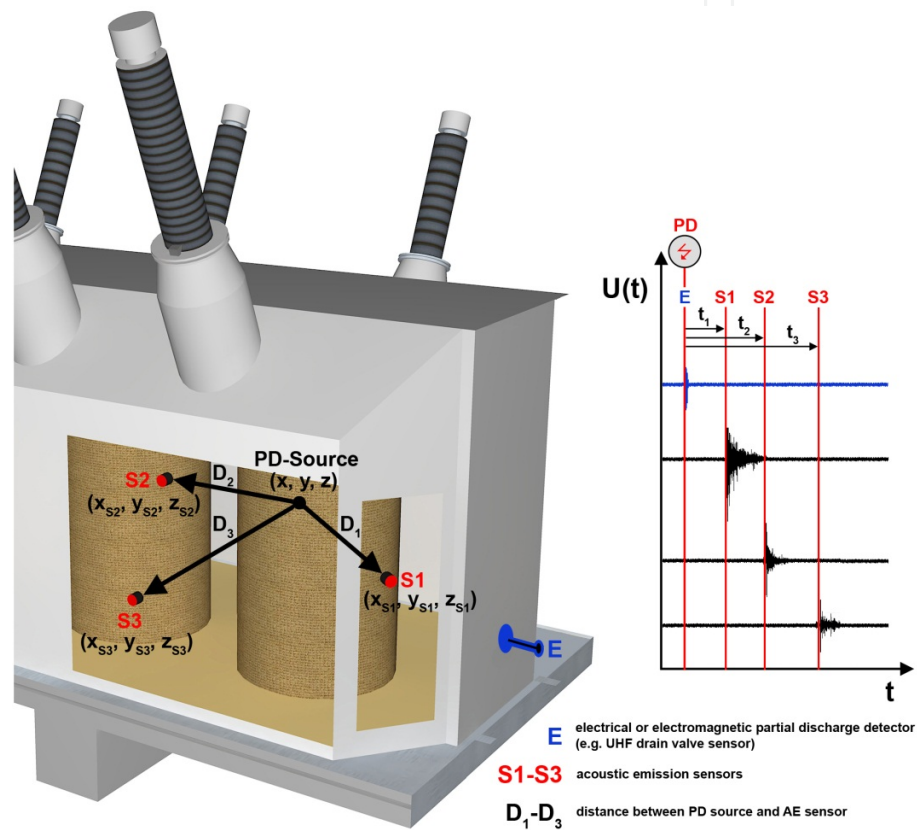
Figure 7. Schematic diagram of Time Difference of Arrival (TDOA) technique with electrical/electromagnetic triggering for partial discharge location in power transformer

5. Examples of partial discharge location and on-line monitoring

5.1. *Case study 1 —* **Short-term monitoring (daily) of the 160 MVA transformer**

Investigations were carried out in a power transformer 125000/220 manufactured in 1978 with the parameters shown in Table 1.

Parameter	Value
Type	RTdxP 125000/220
Voltage	230/120/10.5 kV
Power	160/160/50 MVA

Table 1. Main parameters of investigated transformer

The main reason for performing the partial discharge investigation was a disturbing level of flammable gases in the insulating oil, especially hydrogen. It was noticed just after a flashover which occurred in 2002 in a distribution line that caused a flow of the short-circuit current in the local power system. In successive years the periodic diagnostic measurements revealed a continuous increase of the amount of gases dissolved in the oil. In 2008 a sudden increase of gases in the oil was noticed. The amount of hydrogen exceeded the level of 2000 ppm, and the breakdown voltage of oil decreased to 18 kV, while the permissible value is not less than 50 kV for this type of transformer.

Unfortunately, even after oil treatment process, continuous increase of flammable gases in oil content was still observed. In 2009 SFRA (Sweep Frequency Response Analysis) investigation was made, and the results suggested that the axial displacement, as well as the radial buckling of low voltage and compensating winding was probable. In April 2011 the concentration of hydrogen exceeded 2200 ppm (with permissible value of 350 ppm), and content of CO_2 exceeded 3100 ppm, approaching the permissible value equal to 4000 ppm.

In order to estimate the danger of a transformer failure, the owner decided to make additional measurements of PD using the electrical method. For that reason, the 220/110 kV transmission overhead lines connected to this transformer had to be temporarily switched off. It should be noted that due to very intensive interference originating mainly from the corona on the transmission lines, it was not possible to detect the PD with the use of the conventional electrical method according to IEC 60270. However in this case, the substation was equipped with one transformer only, so when the transformer and the transmission lines were de-energized for the PD measurement system calibration, the interference did not exceed the level of 300 pC. Next, during the PD measurement procedure, when the transformer and the lines were switched on, the interference level changed from 400 pC (110 kV side) to maximum 8 nC (220 kV side), depending on investigated phase and transformer load. Measurements with the electrical method were done for all phases of the transformer (on 110 kV and 220 kV side) using the measuring taps of the bushings.

The measurement procedure was repeated for each transformer phase and consisted of:

1. Disconnection of transmission line and switching the transformer off,

2. Connection of the measuring impedance to the measuring tap of a bushing,

3. Calibration of the measuring system with the use of a standard PD calibrator,

4. Energization of the transformer and detection of the partial discharges.

Transformer phase	Apparent charge [nC]
HV 1	10
HV 2	17
HV 3	11
LV 1	N/A*
LV 2	1
LV 3	N/A*

* No PD activities or PD buried in background noise

Table 2. Maximum value of PD apparent charge registered during test

The result of the PD measurements carried out with conventional electrical method revealed the presence of strong discharges in phase *HV 2* (Table 2). The maximum value of apparent charge reached 17 nC (Fig. 8), however the range of a phase angle, in which the discharges appeared, was mainly from 30° to 90°. In other phases of 220 kV side (*HV 1* and *HV 3*) the PD pulses were also recorded, but their apparent charge value did not exceed 10-11 nC. The range of phase angle was identical as in *HV 2* phase. On the basis of the obtained results it was concluded that the signals observed in phases *HV 1* and *HV 3* were the same as those coming from the *HV 2*, but attenuated, indicating their origin as *HV 2*. In the case of 110 kV side, only the low-energy signals were registered with the apparent charge up to 1 nC, and in *LV 2* phase only.
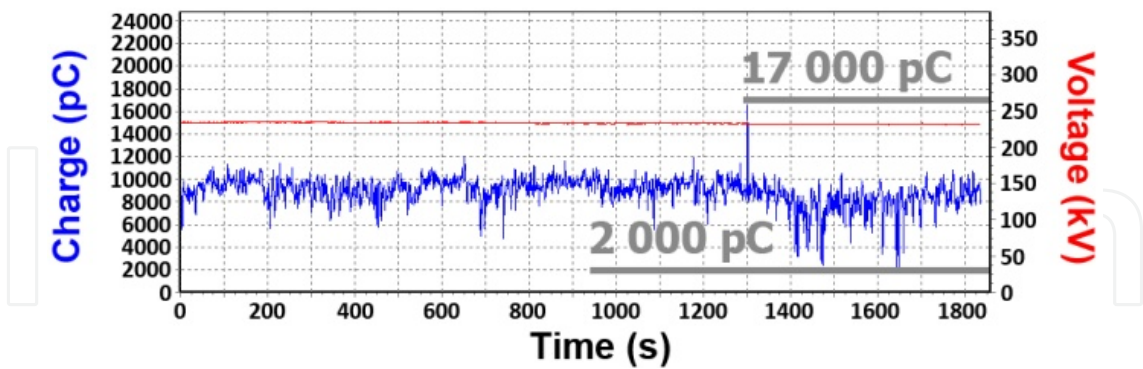

Figure 8. The results of PD apparent charge measurement in phase *HV 2* of investigated transformer.

On the basis of the results obtained with the use of conventional electrical method, it was decided that the procedure of PD source location should be restricted to *HV 2* phase only.

The time of investigation was not limited, as well as it was possible to carry out the continuous monitoring of the apparent charge level. It was also possible to perform the PD location using both the AAT and the TDOA triangulation.

In case of the AAT, in the first step, the measurement points on the surface of transformer tank were chosen and marked. These points formed a measurement grid. In order to increase the reliability of measurements, and simplify the interpretation of the obtained results, the fragments of tank walls with higher thickness were omitted (e.g. corrugated walls and welds). The measurement grid consisted of 36 points, as it is shown in figure 9a.


(a)   (b)
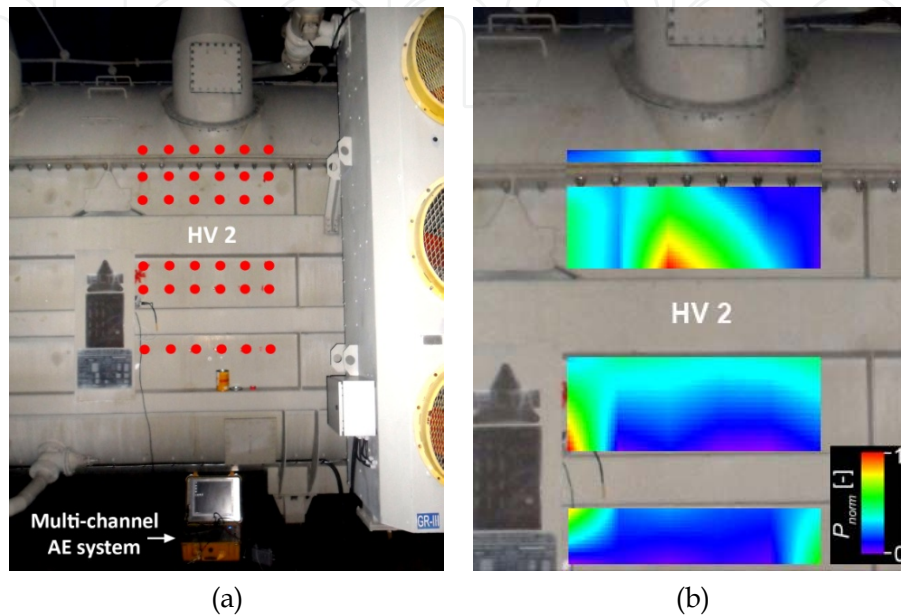
Figure 9. The measurement grid (36 points) used for PD source location with advanced auscultatory technique (a) and the result of PD source location presented as an *Acoustic Emission Map* applied in the picture of the *HV 2* phase of the investigated power transformer (b).

On the basis of the results obtained with the use of AAT, the *Acoustic Emission Map* was prepared and superimposed on a photograph of the transformer tank. The analysis of the *Acoustic Emission Map* image showed that in the HV phase 2 two sources of partial discharges were present (Fig. 9b).

When the acoustic emission measurements with the AAT were finished, a procedure of the PD sources location was initiated with the use of a triangulation technique. The AE sensors were placed on the tank wall in the locations identified by the *Acoustic Emission Map* image analysis. Placing the sensors in region of the strongest AE signals was done to increase the precision of XYZ coordinates' estimation of the PD source location using the triangulation method.

The analysis of the results of PD source location, obtained with the triangulation method showed that both sources of discharges were placed near the symmetry axis of the phase *HV 2* bushing and the transformer tank (Fig. 10a and 10b). On the basis of the investigation results, a hypothesis was assumed that partial discharges were generated inside the insulation of the winding leads or in the support beam that is close to the transformer tank.
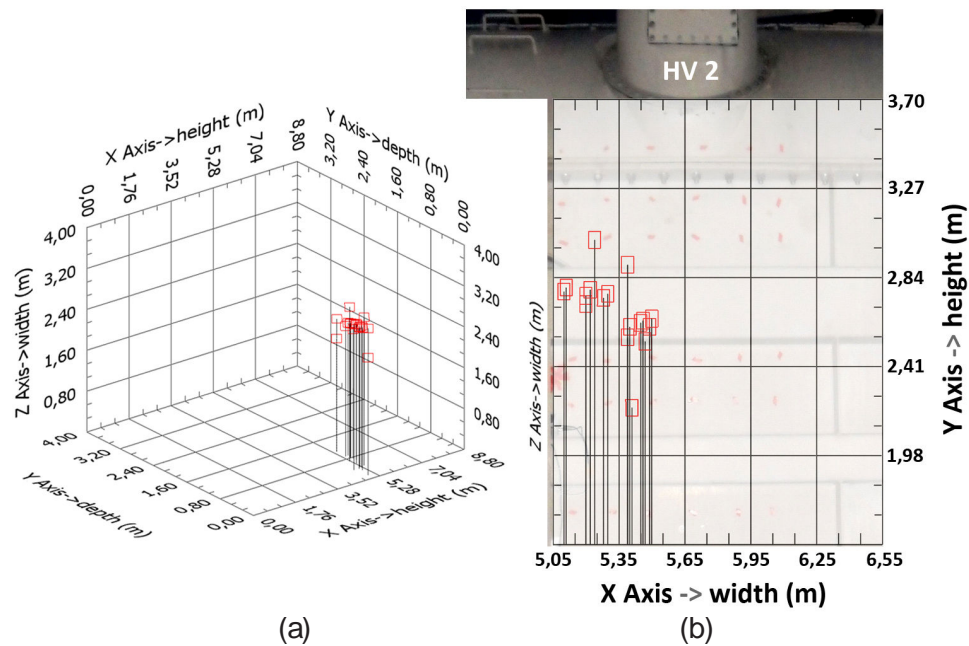
Figure 10. The result of the PD source location obtained with the use of triangulation method presented in the XYZ coordinates system (the XZ plane illustrates the wall of tank from the HV side) (a) and projection of calculated PD co-ordinates (XYZ) to the XZ plane (b).

Based on the obtained results of defect location and the analysis of the external structures of the transformer tank, the places, where acoustic emission sensors of monitoring system should be mounted, were selected (Fig. 9b). Due to the fact that AE sensors were placed close to located defect, on each of the four channels a similar number of acoustic events was recorded (Fig. 11). The amplitude of the signal recorded by each sensor was similar as well.

The same was also the average amplitude of the signal recorded by each sensor (Fig. 12). However, when looking at the distribution of number of AE events, it can be noted that daily activity profiles of the partial discharges recorded by pairs of sensor (00&01 and 02&03) were similar. This fact suggests the existence of two defects, which was already mentioned after the analysis of the location results with the use of *Advanced Auscultatory Technique* (see Fig. 9b).
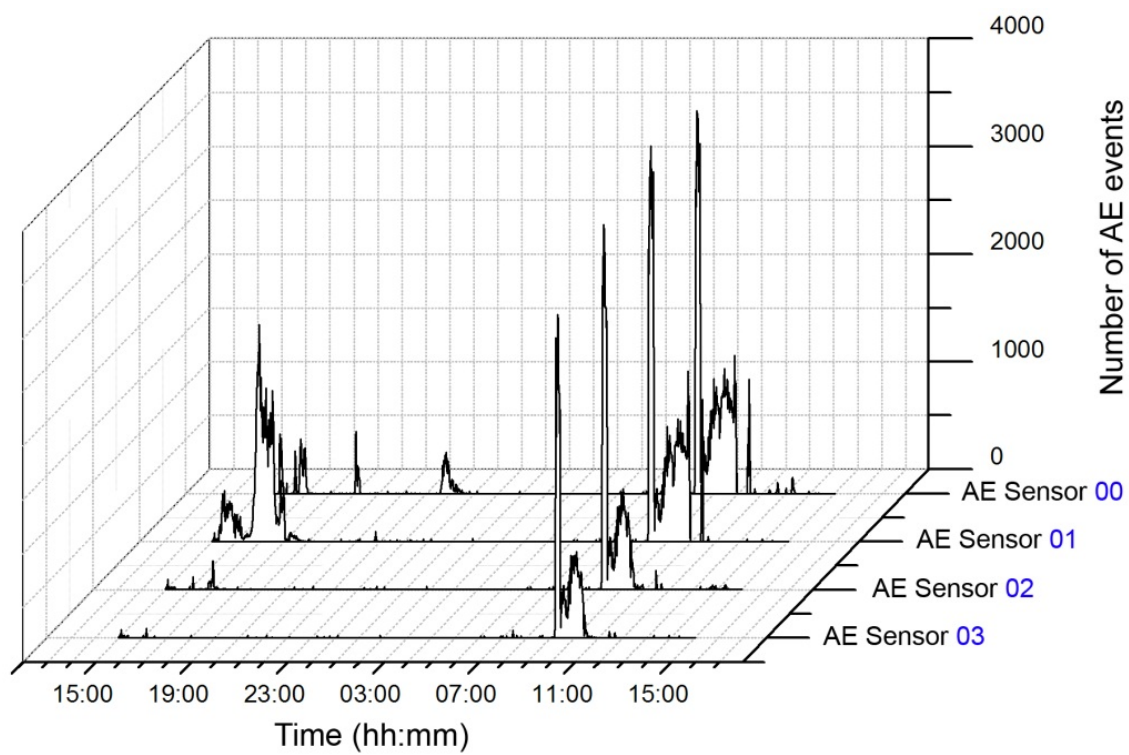
Figure 11. The number of AE events registered during daily monitoring of 160 MVA transformer
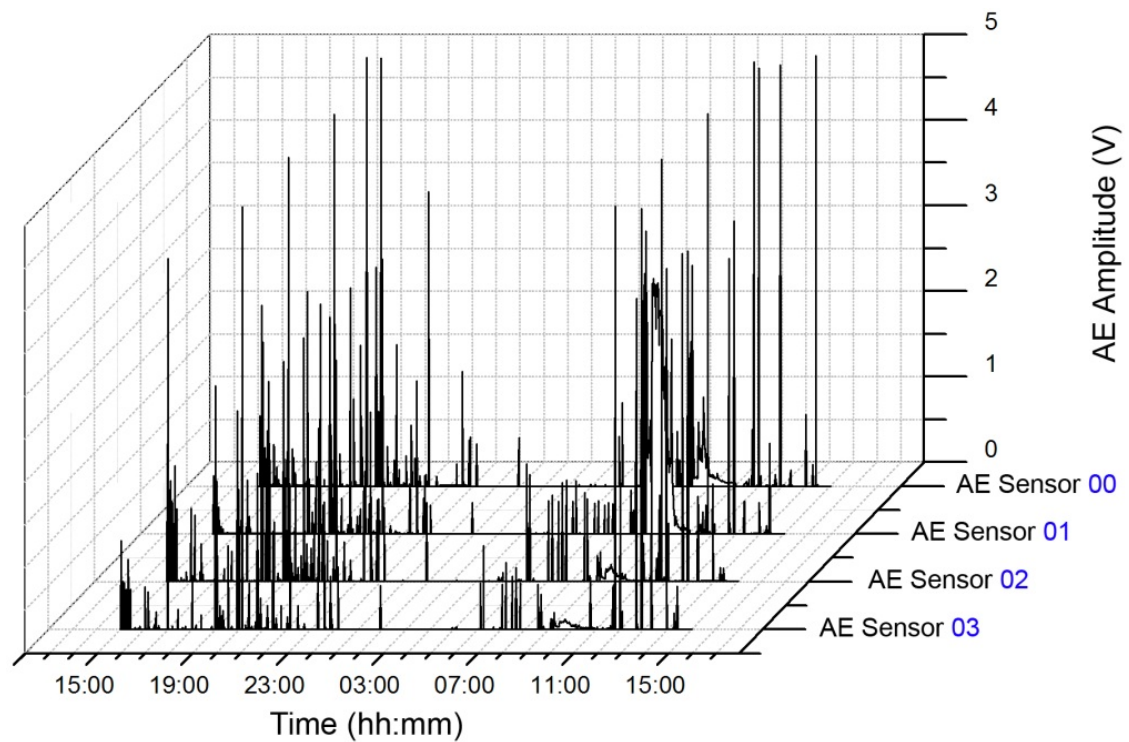
Figure 12. Amplitude of AE events registered during the daily monitoring of 160 MVA transformer.

Further interesting conclusions arise when comparing both the number of events and the average amplitude of the acoustic signal with daily load of the unit (Fig. 13). One can observe that the increase in the load is associated with increase of intensity and amplitude of partial discharges. Load peaks, occurring at 21:00 and 12:00, are accompanied by the largest PD intensity and highest average amplitude of registered acoustic signals. Probably, the temperature increased closed to defect, which was a consequence of the growth in the value of the current, causing intensification of the partial discharge phenomenon. Analysis of the impact of voltage changes caused by tap changes of the autotransformer, did not show any significant correlation with respect to the recorded acoustic signal (voltage change were small indeed).
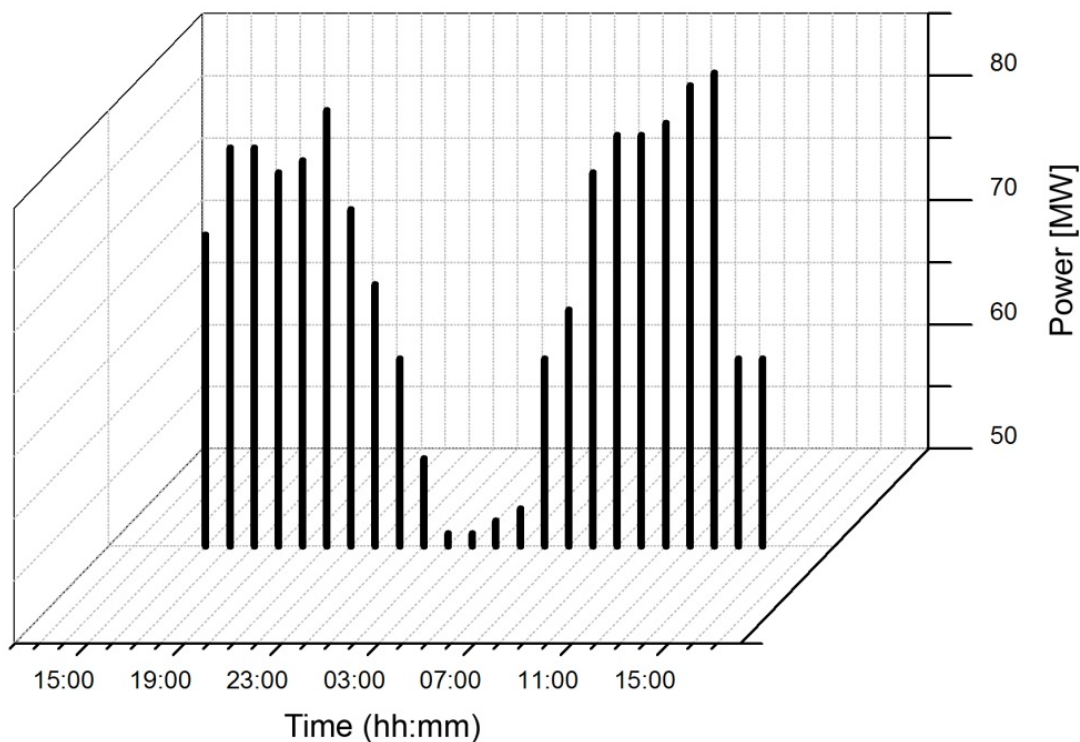
Figure 13. The value of daily load of the monitored transformer, registered in SYNDIS ES system

Observation of daily profile of PD activity changes also shows the advantages of on-line monitoring and imperfections of the standard approach to measuring partial discharges.

As one can observe in Fig. 11-12, the time of measurement can determine the quality of the analysis. During the day, both periods occurred in the monitored unit: extinction of partial discharges and their particular intensification.

Therefore one can conclude, that the choice of date and time for the implementation of periodic diagnostic tests by AE method (lasting usually no longer than a few hours) may have a fundamental importance for correct and reliable assessment of transformer insulation system. Of course, due to the stochastic nature of the partial discharge phenomenon, the most reliable results are obtained by monitoring the unit for a period of time at least one day.

5.2. *Case study 2 – Short-term monitoring (weekly) of 250 MVA transformer*

A reason for installing the monitoring system to 250 MVA transformer was to observe from the beginning of 2011, the systematic increase of dissolved gases in oil (mostly hydrogen). The same year, in June, the location of the partial discharge sources by means of acoustic emission method was performed.

During the tests, several areas were located on tank in which recorded acoustic emission pulses were characterized by high amplitude. In the case of the lower voltage side (110 kV), repeatable pulses with the largest amplitude were recorded close to neutral point bushing (*N*). In addition, on the same side, sporadically occurring high amplitude PD pulses localized in phase *LV 1* and *LV 3* were recorded. During the measurements, any discharge pulses in phase *LV 2* were not registered (Fig. 14). In the case of the high voltage side (400 kV) sporadically occurring partial discharge pulses were also recorded, however, they were characterized by much smaller amplitude than it was in the case of the low voltage side.
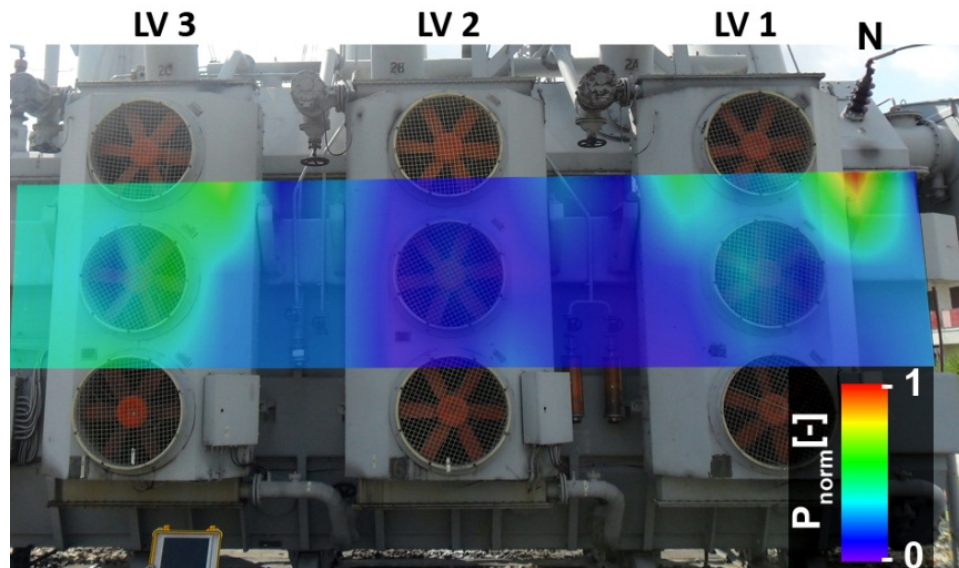

Figure 14. Results of PD source location (*Acoustic Emission Map*) obtained using advanced auscultatory technique (AAT) on low voltage side of the 250 MVA transformer

Due to further systematic increase in the level of hydrogen dissolved in oil and the alarming results of the detection and location of partial discharges, in December 2011 the transformer owner decided to install a monitoring system for a period of one week. Based on the results of the location, obtained before, three AE sensors have been mounted on the tank on the low voltage side near selected areas of greatest loudness (phase *LV1* – sensor '02', phase *LV3* – sensor '00', proximity to neutral point insulator – sensor '03'). The last sensor '01' was mounted in phase *LV 2* (as reference sensor), where the test results showed that it is free from partial discharges. Such arrangement of AE sensors allowed the simultaneous monitoring of all phases of the transformer, with particular emphasis on critical points, which were fixed on the tank before. In the characteristics of the number of acoustic events registered during the weekly monitoring of the transformer were

summarized in figure 15. In turn, on figure 16 the values of the oil temperature in top layer and voltages of monitored transformer registered in SYNDIS ES system were presented.
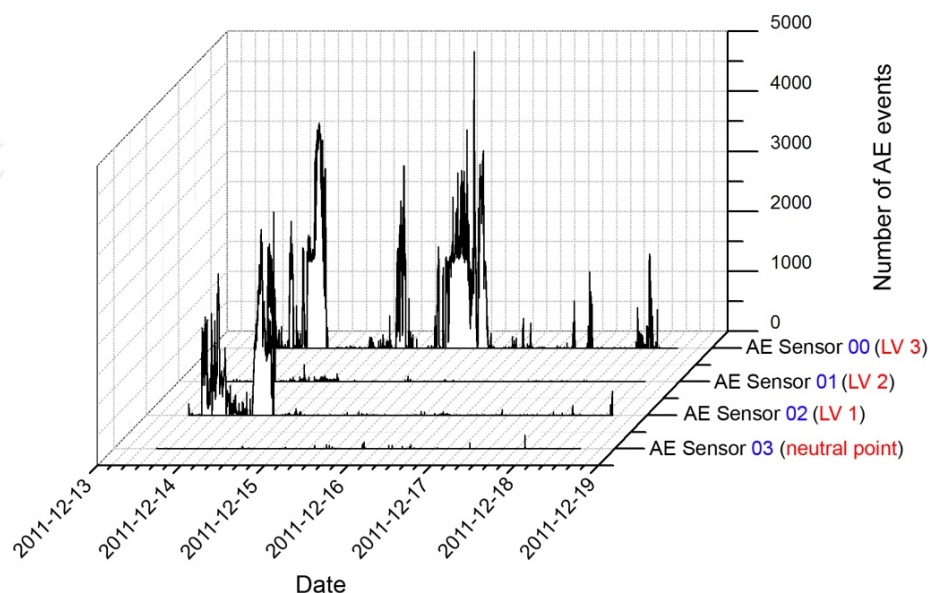
Figure 15. The number of EA events registered during the weekly monitoring of tested 250 MVA transformer
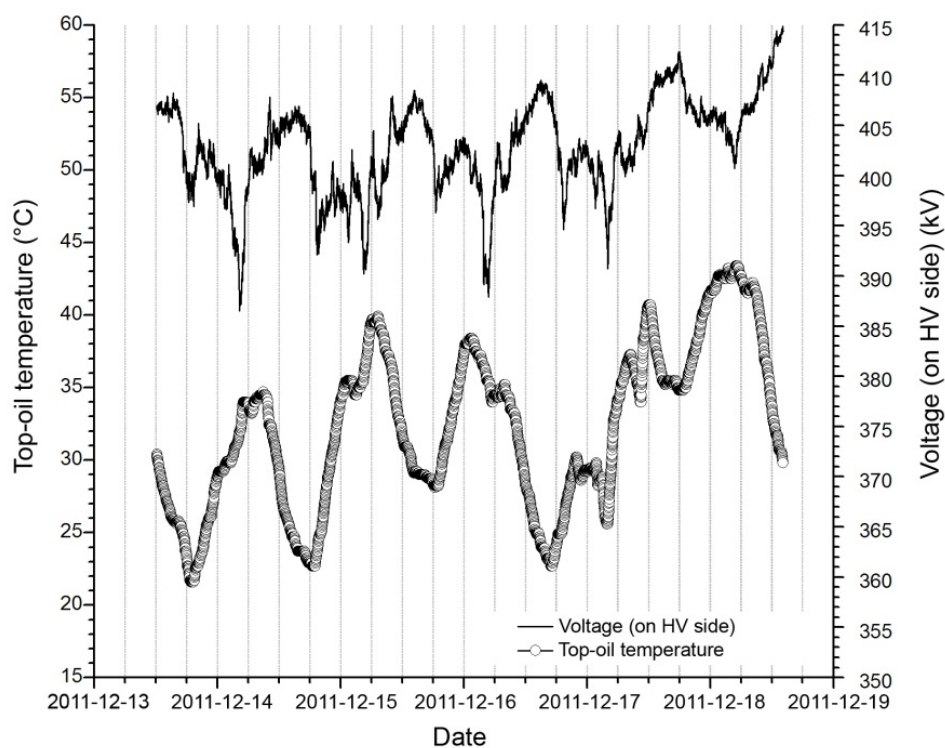

Figure 16. The value of the top layer of the oil temperature and voltages of the monitored 250 MVA transformer registered in SYNDIS ES system

Analysis of the characteristics showing the number of AE events recorded by the monitoring system confirmed the presence of partial discharges in phase *LV 1* and *LV 3* and the absence or presence of a few discharges in phase *LV 2* and close to neutral point bushing (Fig. 15). Monitoring showed that pulses with the highest intensity and energy are generated in phase C. The recorded PD pulses were unstable, and their ignition took place only in periods of voltage growth (Fig. 16). Moreover, it was noted that the moment of PD ignition correlates with temperature minima of top layer of oil, which may have a relationship with some dynamic changes in moisture at the interface of oil-paper insulation, described for example in (Borsi & Schroder, 1994; Buerschaper et al., 2003; Sokolov et al., 1999).

5.3. *Case study 3* — **Long-term (continuous) monitoring of 330 MVA transformer**

In this case the choice of the research object, on which continuous monitoring was tested, did not resulted from bad condition of the transformer. The primary purpose was integration of the PD monitoring system with the superior system (SYNDIS ES) and evaluation of opportunities for their cooperation. However, as in other cases, place of sensors location were selected basing on previously carried out detection and PD sources location using *Advanced Auscultatory Technique* (Fig. 17).
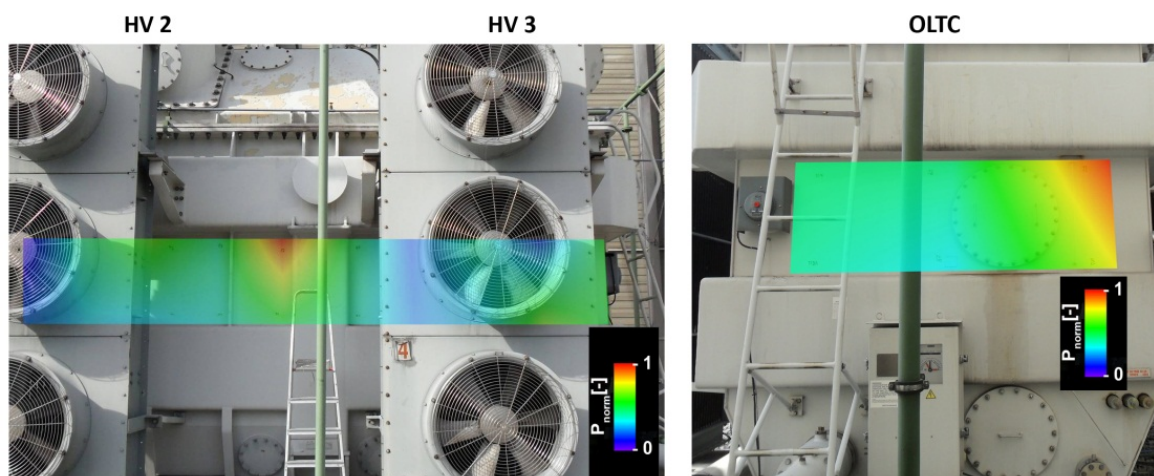

Figure 17. Results of PD source location (*Acoustic Emission Maps*) obtained using advanced auscultatory technique (AAT) on HV and OLTC side of the 330 MVA transformer

Acoustic sensors were installed in each HV-phase and on the tank of on-load tap changer (OLTC), in the place, where the pulses with the highest amplitude were recorded.

For the moment, the system worked continuously and without failure for about 9 months. At that time, it registered several periods of partial discharge activity, but their low intensity not suggested the possibility of a serious threat. However, the ability to correlate, e.g. the moment of PD initiation with different parameters recorded by the SYNDIS ES system (oil temperature, load, voltage etc.), seems to be interesting, especially from a scientific point of view and the possibilities for development and improvement of inference rules implemented in the software of monitoring system.
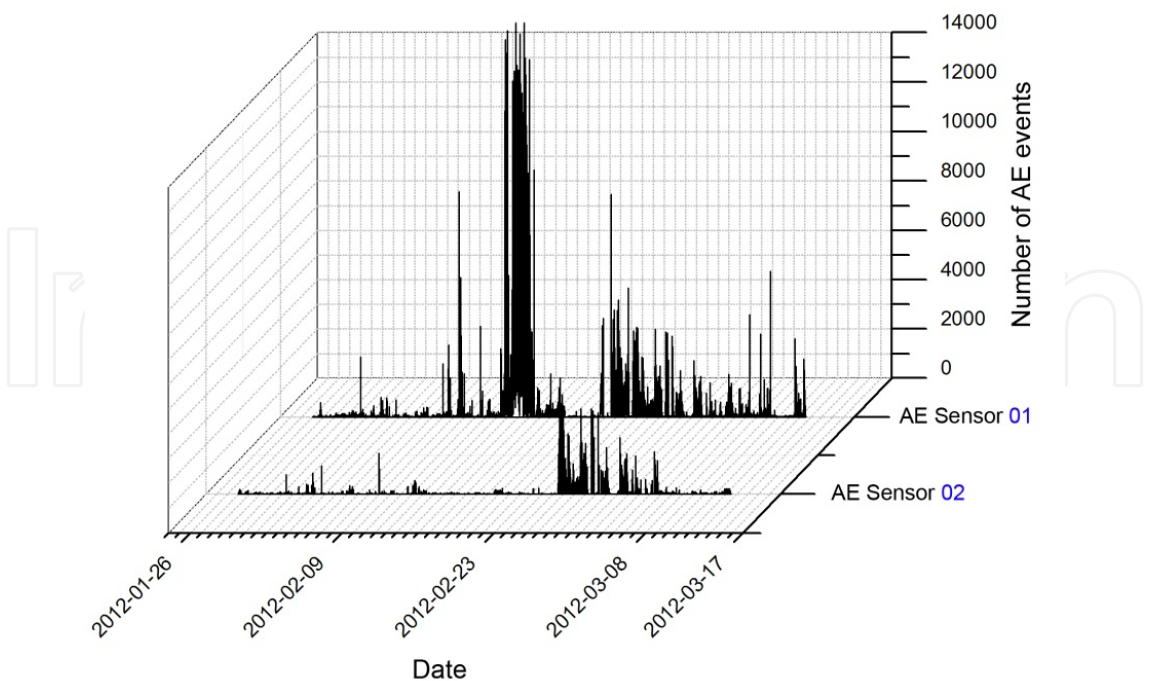
Figure 18. The number of AE events registered on 330 MVA transformer, where the long-term test of partial discharge monitoring system was carried out.
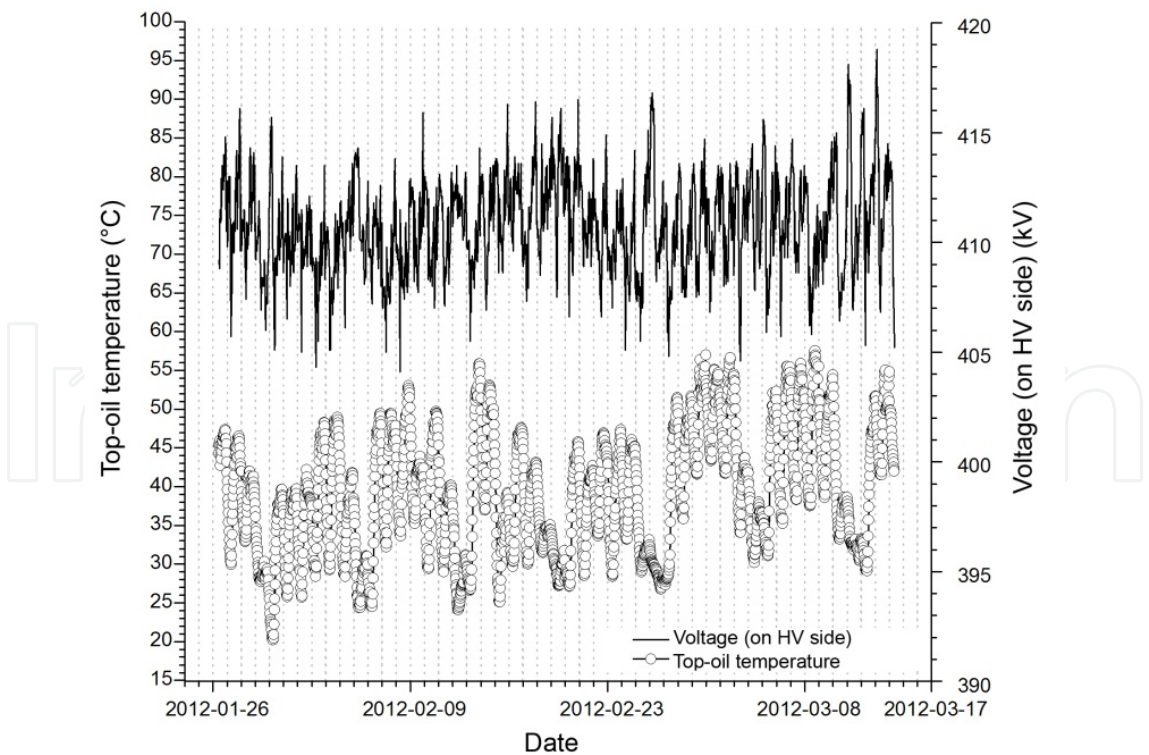
Figure 19. The oil temperature at top layer and values of voltages of the monitored 330 MVA transformer registered in SYNDIS ES system

For example, figure 18 shows the number of PD pulses registered by two sensors with numbers '01' and '02', installed respectively in phase *HV 1* and *HV 2*. As one can observe, partial discharges were transient, but comparison with other parameters, such as temperature and voltage (Fig. 19), allows to detect a correlation. As it was described in the previous case, the moment of PD initiation and growth of its intensity were connected not only with an increase in voltage, but at the same time, with relatively low value of oil temperature (20-30°C). Particularly high partial discharge activity has been reported in cases, in which the period of oil cooling and at the same time the growth of voltage lasted at least several hours. In the phase *HV 1* (sensor '01') this situation took place from 25 until 27 February, and in phase *HV 2* (sensor '02') between 12 and 13 day of the same month.

6. Conclusions

The chapter presents detailed description and features of the *Time Difference of Arrival* (TDOA) technique and new *Advanced Auscultatory Technique* (AAT) for location of partial discharge sources, as well as some examples of its practical application in power transformer diagnostics.

The developed by the authors *Advanced Auscultatory Technique* constitutes a synergistic combination of two diagnostic methods: (i) the acoustic emission (AE) and (ii) the conventional electrical PD detection method according to IEC 60270.

The presented research results proved numerous advantages of the AAT, among which the most important are:

- reduction of influence of partial discharge energy fluctuations on energy of registered AE pulses, which are the main reason of the PD source location errors with the standard auscultatory technique,

- clear and readable presentation of the fault location results in form of a high-resolution intensity graph (Acoustic Emission Map),

- the possibility of correlation between AE parameters and apparent charge,

- uncomplicated and quick PD location technique, particularly useful for transformer manufacturing plants and repair companies equipped with electrically shielded HV laboratory.

The partial discharge online monitoring in power transformer based on AE method was another important topic covered in the chapter.

The presented results largely confirmed the advantages offered by the partial discharge monitoring using the acoustic emission method, of which the most important are:

- ability to assess the profile of daily, weekly or monthly partial discharge activity,

- possibility of linking the partial discharge activity with other events or parameters recorded by the service station or other systems monitoring transformer work,

- ability to assess the dynamics of defect development,

- elimination of the interpretative errors which might arise in the standard and short-lived measurement procedures, and

- possibility of partial discharge sources location.

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