Partial discharges location in power transformers using piezoceramic sensors

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Article Info

ABSTRACT

The detection and the spatial localization of partial discharges in high-voltage electrical machines are considered as an effective method in predictive maintenance that can provide valuable information on the health of the insulation system and allow to determine accurately the location of the risky insulation elements, which in turn will avoid any premature equipment's deterioration by scheduling preventive maintenance action. After confirming in a previous published paper the efficiency of a new generation of piezoceramics sensors (high temperature ultrasonic transducers) to detect and characterize partial discharges, we are going to investigate, in this work, a second potential of this technology to locate the partial discharge sources by relying on its ability to detect acoustic signals emitted by partial discharge sources. We will present experimental results, demonstrating the effectiveness of these sensors to locate partial discharges sources and, we will also present an algorithm for calculating the partial discharge foci, based on the acoustic wave flight time.

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1. INTRODUCTION

Power transformers are major electrical components that play an important and strategic role in the energy distribution network. They minimize Joule's losses and thus facilitate energy distribution by transforming low tensions into high ones in the power lines and then lowering them again to meet the users need. Due to their extremely important position, the unexpected shutdown of power transformers would have serious economic, social and environmental repercussions. Therefore, ensuring the prolongation of their useful life and the monitoring of the performance of the transformers is critical. In fact, a major issue affecting the sustainability of power transformers is the gradual and systematic deterioration of the insulation system as showcased in statistical and empirical studies [1, 2].

Once in service, the insulation system is exposed to partial discharges, defined as localized electrical currents that can only partially bypass the spacing between electrodes, i.e. the insulation volume, that are mainly caused by local electrical stress concentrations. Often such discharges appear as impulses that last less than 1 μs [3]. The PD can be created within different types of insulation (solid, liquid, gas) and are accompanied by small sparks full of electrons and ions that attack the insulation. Thus, the organic materials constituting the bulk insulation systems (mineral oils, epoxy polyester resins, etc.) degrade during this attack by splitting certain chemical bonds such as carbon-hydrogen bonds. Over time, this can lead to an eventual

dielectric breakdown [4-6]. A confirmation of the performance of insulating materials is essential, from which the need of a real time monitoring system is born [7-9]. Knowing that the evolution of PD activity is symptomatic of the insulation state, their patterns characterization and the localization of their foci will provide useful information to the predictive maintenance system [10-12].

Existing research focus on the identification and the characterization of these PDs. However, studies on their localization are as relevant. The PDs localization allows maintenance plans to be more oriented and efficient. In recent years, there has been a strong trend towards the development of new methods for the detection and location of partial discharges for various applications in electrical engineering [7, 13-17]. There are existing detection methods, electrical and chemical ones that have proven to be reliable diagnostic tools. Nevertheless, they have their limitations. Electrical methods do not allow the detection of foci of discharges (except for UHF antennas) and their sensitivity decreases with increasing capacitance of the tested object, such as high-voltage transformers [18]. In respect of chemical methods, although recognized as valuable tools, they are also unable to locate the foci of partial discharges and they also cannot be used while the transformers are still in service. On another hand, there are acoustic methods that are also commonly used. Acoustic techniques are well recognized and used in failure analysis and non-destructive testing [19].

More specifically, in the analysis of PDs, they are used extensively in the detection and localization of PDs in high voltage equipment such as rotating machinery and transformers [14, 20-24]. In fact, Piezoceramic films performing at high frequency (High Temperature Ultrasonic Transducers-HTUTs) have been developed by Industrial Materials Institute, National Research Council of Canada [25, 26]. These piezoceramics are made of a combination of BIT (bismuth titanate), and PZT (lead zirconatetitanate). The potential of this technology is based on a set of advantages. It offers a lightweight, miniature and malleable structure (thickness 40-120 μm), which gives it great flexibility and the ability to be bonded (or even 'painted') on different surfaces. It can be used in tough conditions. It also offers a large range of temperatures (-150 °C to 400 °C) and a high dielectric constant $\varepsilon_r \approx 90$. In addition, these probes require no electrical coupling and the cost is very affordable. For more details on elaboration methods and the various properties of these sensors, we refer the reader to [25]. Figure 1 shows some BIT/PZT films.

Figure 1. Piezoceramic sensors HTUTs

Thanks to their inherent features, these piezoceramic films provide an excellent economic alternative for use in the detection and location of partial discharges. The efficiency of these Piezoceramic films in detecting and characterizing PDs was confirmed in our previous paper [27]. In this paper, we study piezoceramic sensors' capacity to locate partial discharges using acoustic wave detection. We will also provide a method based on the acoustic wave flight time to calculate the PD foci coordinates. The validation of this new technology would bring the monitoring of high-tension systems to higher efficiency level by opening the way for the design of an online PD measurement and analysis system. As a matter of fact, the new technology of piezoceramic films responds to the need of implementing for each transformer a reliable real-time monitoring system whose objective will be the continuous assessment of its availability throughout its useful life, the localization and recognition of PDs events at an early stage, and finally the determination of appropriate maintenance plans [11, 21, 28].

In the sections below we will first present the mathematical solution to the equations of the localization system based on the acoustic wave's flight time. Afterward, we illustrate the experimental setup, as well as the raw and filtered signals captured by the piezoceramics. In the last section, we will analyze the results and present the calculation of the position of the discharges sources based on the acoustic wave's flight time.

2.   ACOUSTIC METHODS FOR LOCATING PARTIAL DISCHARGES

The acoustic technique method is based on the detection of acoustic signals emitted by the rapid release of energy from a partial discharge source. The discharge acts as a point source of transient elastic waves in the ultrasonic range, typically between 20 kHz and 1 MHz, propagating through the insulation system. These can be detected on the walls of the test object using sensors typically with a band width centered at around 60 kHz or 150 kHz [21, 29].

The ability of determining the location of a discharge is, without a doubt, the biggest advantage of the acoustic method. The principle of localization can be either based on the measurement of the arrival time of the signal to the sensors [30-32], or on the measurement of the acoustic signal's intensity. We will limit ourselves in this study to developing the first method using the acoustic wave's flight time principle.

In order to come up with a solution to solve the problem of locating PD, a minimum of four (4) sensors are required given that the system to solve contains four unknowns : the departure time of the acoustic wave, t_0, and the coordinates (x, y, z) of the discharge location. Figure 2 shows a schematic diagram of the localization principle.
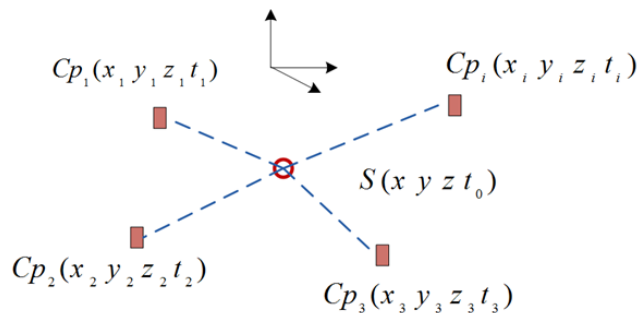

Figure 2. Schematic diagram of the localization principle

Let r_i be the distance between sensor i and the source point of coordinates x, y, z. Its equation can be written as (1):

$$r_i^2 = (x - x_i)^2 + (y - y_i)^2 + (z - z_i)^2 \tag{1}$$

With c being the speed of sound in the dielectric fluid, if we assume uniform movement, the distance r_i traveled by the wave at time t_i would be given by (2):

$$r_i = c(t_i - t_0) \tag{2}$$

With t_i representing the moment of arrival of the wave to the sensor i and t_0 being the moment of departure from the source. To eliminate the unknown t_0, we can calculate the difference in the distance from the source between the i and the sensor, $d_{i,j}$, using the (3).

$$d_{i,j} = r_i - r_j = ct_{i,j} \tag{3}$$

With $t_{i,j}$ being the difference of flight times for the two sensors. The difference of the distance squares r_i and r_j gives:

$$r_i^2 - r_j^2 = h_i - h_j + 2x(x_j - x_i) + 2y(y_j - y_i) + 2z(z_j - z_i) \tag{4}$$

with:

$$h_i = x_i^2 + y_i^2 + z_i^2 \tag{5}$$

To simplify writing, we can express $x_i - x_j$, $y_i - y_j$ and $z_i - z_j$ by $x_{i,j}, y_{i,j}$ and $z_{i,j}$. Combining (3) and (4), we obtain:

$$x_{i,j}x + y_{i,j}y + z_{i,j}z = \frac{1}{2}\left(h_i - h_j - d_{i,j}^2\right) - d_{i,j}r_j$$

(6)

Applying (6) applied in the case of four sensors j, i, k, f defines a system of linear equations allowing to solve the x, y, z coordinates in relation to the r_j distances:

$$\begin{pmatrix} x \\ y \\ z \end{pmatrix} = \begin{pmatrix} x_{i,j} & y_{i,j} & z_{i,j} \\ x_{k,j} & y_{k,j} & z_{k,j} \\ x_{f,j} & y_{f,j} & z_{f,j} \end{pmatrix}^{-1} \times \left[\frac{1}{2}\begin{pmatrix} h_i - h_j - d_{i,j}^2 \\ h_k - h_j - d_{k,j}^2 \\ h_f - h_j - d_{f,j}^2 \end{pmatrix} - r_j \begin{pmatrix} d_{i,j} \\ d_{k,j} \\ d_{f,j} \end{pmatrix} \right]$$

(7)

The substitution of this solution $(x, y, z)_{r_j}$ into the equation (1) for $i=j$ yields a quadratic equation for r_j. The positive root is reintroduced into equation (7) to obtain a final solution for the *x, y, z* source coordinates. In the case of *n* sensors, the system (7) becomes statically indeterminate; the number of equations being greater than the number of unknowns. In such situations, an iterative solution using a least square principle can be obtained or by using another algorithm which minimizes the objective function [22].

3.   EXPERIMENTAL RESULTS

The Figure 3 presented below is an illustration of the breadboard used in this investigation. Discharge events due to an air bubble in dielectric oil were recorded by four sensors located at four sides of a PMMA case. These sensors are directly connected to the channels of a digital oscilloscope. The Figure 4 illustrates the geometric arrangement of the four sensors on the bench box.
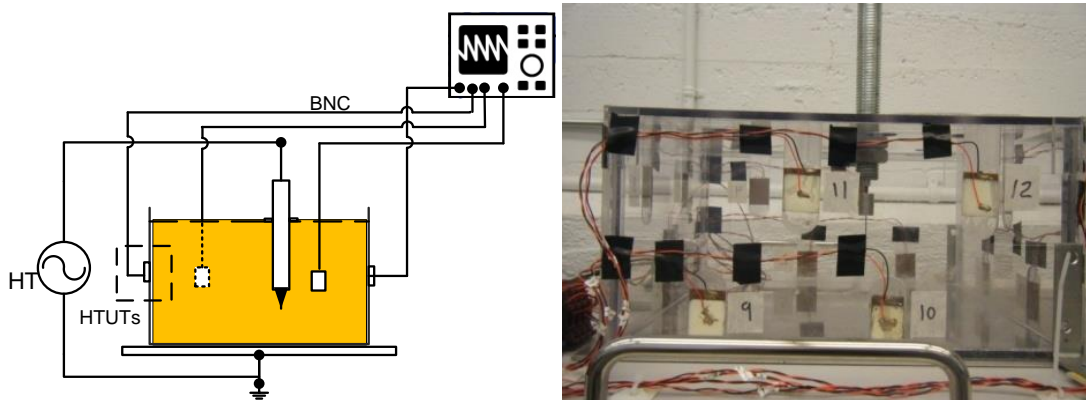

Figure 3. Experimental setup

To cover the frequency range of sound waves, the following measurement parameters and post-treatment parameters were used:

a.   Time per division: $\Delta t = 100$ μs,

b.   Sampling frequency: $f_e = 10$ MHz,

c.   Wavelet type: Db8, and Max decomposition level: 10.

As expected, the raw signals recorded by the four sensors show that they have abroad band frequency response that can go up to the MHz range. To study the signal in the frequency range of acoustic emissions, wavelet decomposition with Db8 up to the 10th level can be used in order to restrict the signal frequencies to those included in the range of interest [20-200 kHz]. The Figure 5 showcases the frequency response of the four sensors within this range.
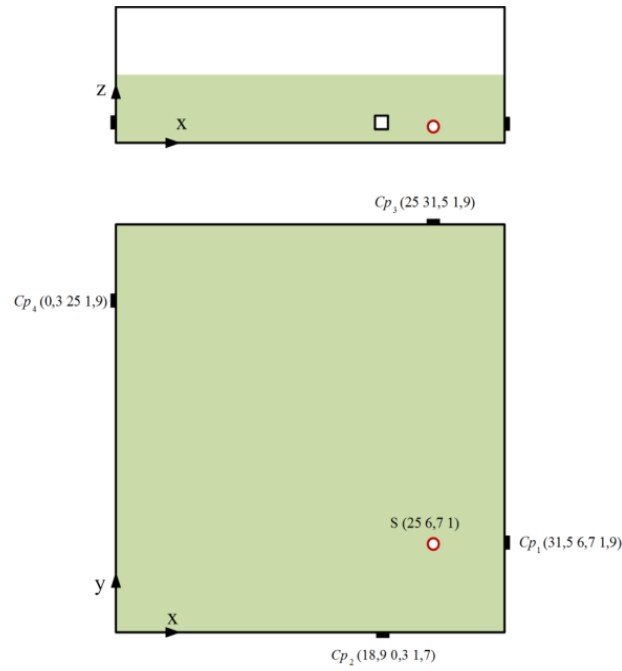
Figure 4. Geometrical disposition of the sensors and the source
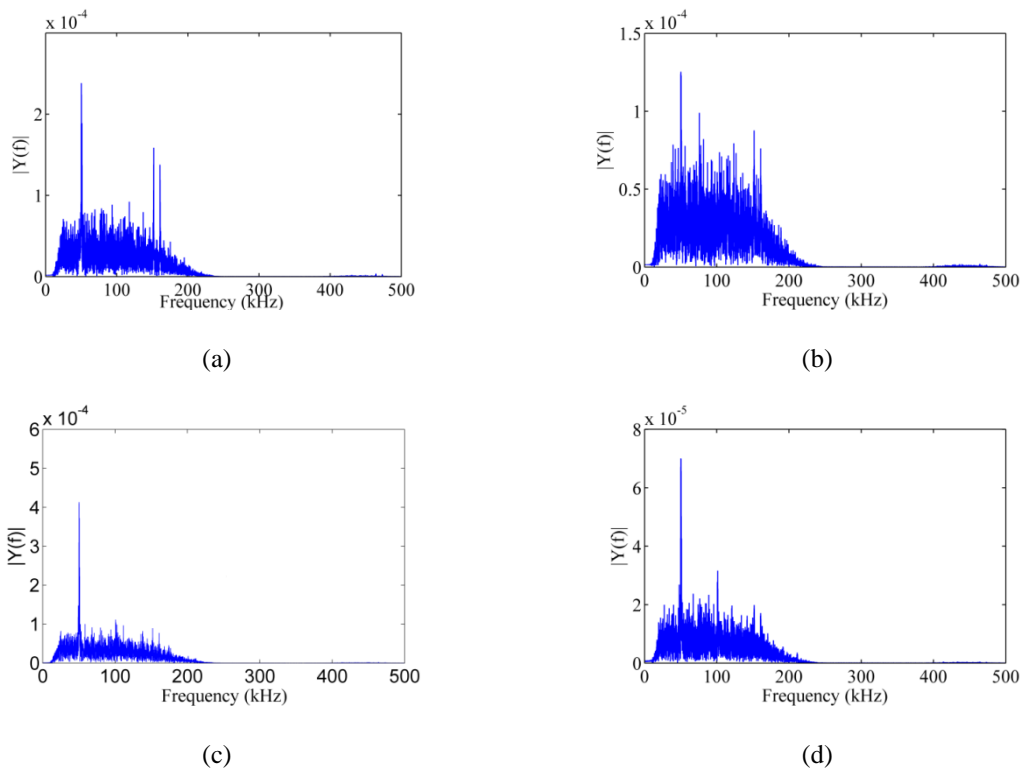

(a)

(b)

(c)

(d)

Figure 5. Frequency responses of the four sensors in intervals of [20 kHz, 200 kHz]

The four figures show that the maximum energy of these sensors' frequency response is around 50 kHz. Therefore, for the discharge source localization, this will be the frequency of interest. A filtration and reconstruction of the signal according to detail 7 of the previous decomposition by wavelets, allows for the extraction of this frequency zone as displayed in Figure 6.
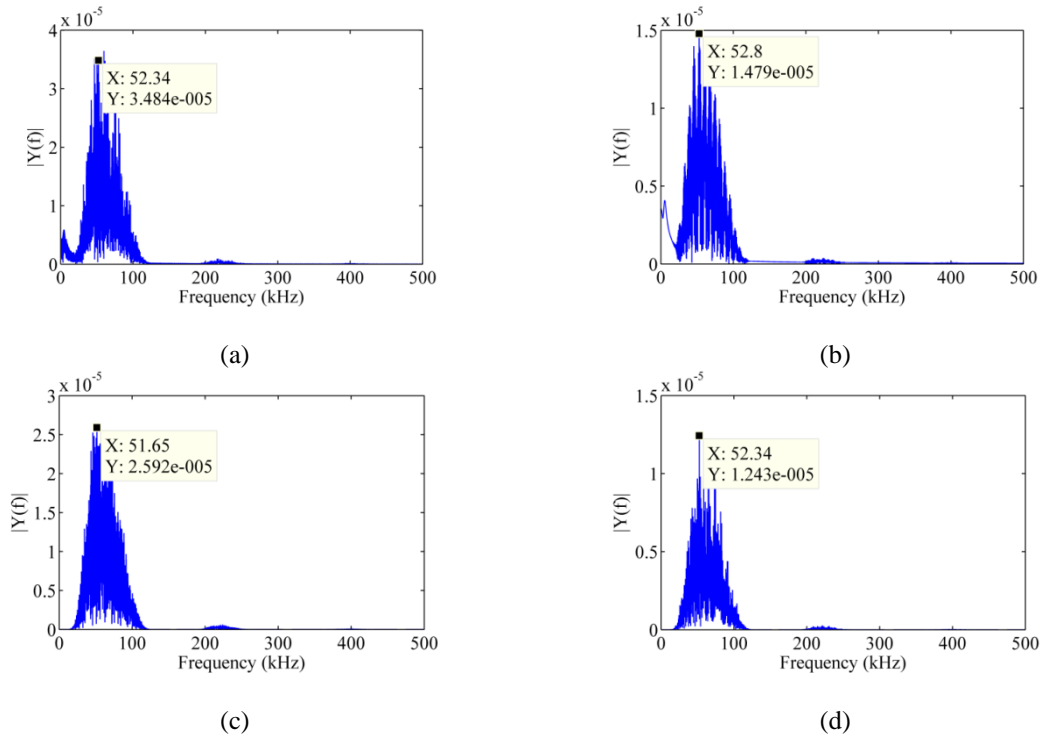
Figure 6. Frequency spectrum of level 7 detail

3.1. Calculation of source coordinates

To validate the localization method previously described, a discharge source was placed in a pre-established coordinate position (x, y, z) and the difference in flight times $t_{i,1}$ as compared to sensor 1, are determined experimentally. Table 1 presents the different coordinates of the four sensors used, along with their source. Since the different z coordinates corresponding to the sensors and the source are relatively close, we can consider the situation as being a two-dimensional problem. Figure 7 shows an example of the filtered signals recorded simultaneously by the four sensors, corresponding to level 7 detail.

In the four figures, we notice that there is a high intensity pulse followed by one of lower intensity. The first pulse occurred at almost the same time for the different sensors. We can therefore assume that pulse is related to the electromagnetic wave. The second pulse arrives approximately at a velocity in the range of the speed of sound, as shown in Table 2 which summarizes the various test results and gives approximate values for the wave propagation velocity for the four sensors. We conclude that this last pulse is an acoustic wave.

Table 3 shows results for the calculation of the discharge source position using the algorithm previously described. The value of the speed of sound used for the calculation was c=1500 ms^{-1}. The calculation yields an estimation of the source position with a margin error of 2 cm.

This result confirms a second potential benefit from the use of these sensors - the ability to estimate the discharge source location by the simultaneous acquisition of the electrical and acoustic signals. The fact that we can simultaneously detect the acoustic signal and the high frequency electric signal emitted by the PDs reduces the number of sensors required to solve the problem to 3. In fact, the unknown t_0 can be estimated by the arrival time of the electromagnetic wave. We would like to also add that these results were obtained on a simple test bench with no signal amplification. We believe that the use of several sensors and a signal amplifier can provide even more accurate results.

Table 1. Sensors and source coordinates positions

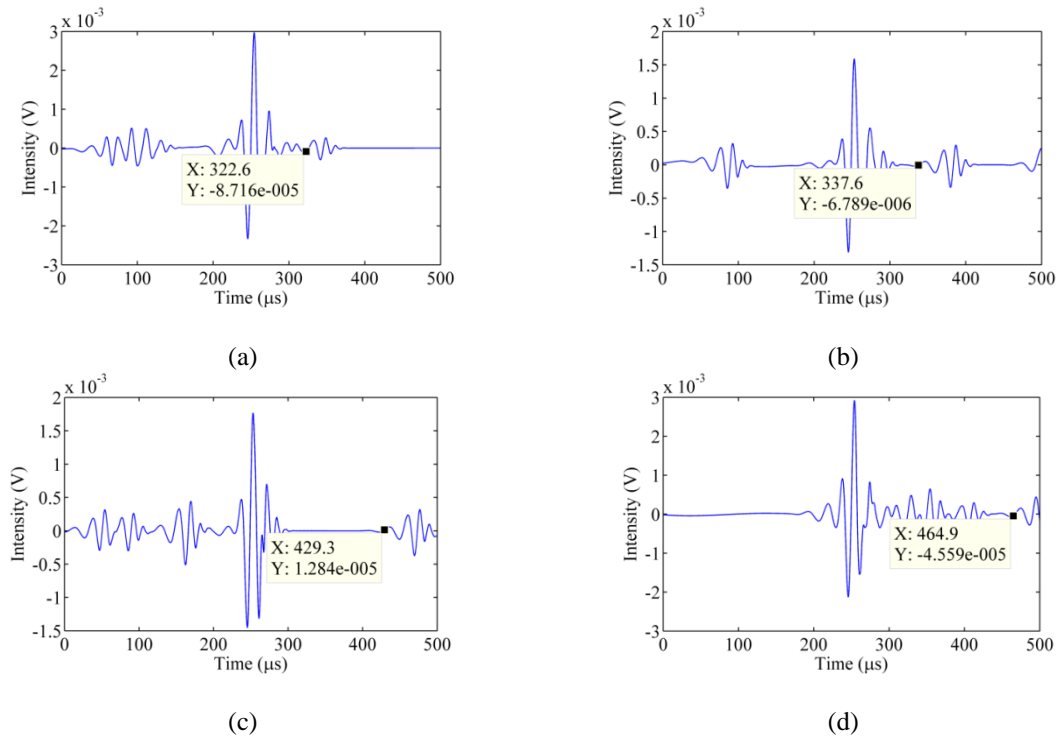| Sensors and Source	Coordinate X (cm)	Coordinate Y (cm)	Coordinate Z (cm)
Sensor 1	31.5	6.7	1.9
Sensor 2	18.9	0.0	1.7
Sensor 3	25.0	31.5	1.9
Sensor 4	0.0	25.0	1.9
Source	25.0	6.7	1.0

Figure 7. Example of 4 sensor signals with arrival times

Table 2. Experimental times $t_{i,1}$ and corresponding calculation for the speed of sound

Sensor	Distance r_i (cm)	Arrival time t_i (μs)	$t_{i,1}$ (μs)	$d_{i,1}$ (cm)	Estimated speed(ms^{-1})
1	6.6	322.6			
2	9.0	337.6	15.0	2.4	~1600
3	24.8	429.3	106.7	18.2	~1706
4	30.8	464.9	142.3	24.2	~1701

Table 3. Calculation results for the source position

Positions	Coordinate X (cm)	Coordinate Y (cm)	Δr (cm)
Real source position	25.0	6.7	-
Calculation 1	24.3	8.1	1.5
Calculation 2	24.1	8.6	1.6
Calculation 3	23.7	7.7	2.3
Calculation 4	23.4	8.4	1.8
Average calculated position	23.87	8.2	1.9

$_* \Delta r = \sqrt{\left(\Delta x^2 + \Delta y^2 \right)}$

4.   CONCLUSION

In addition to efficiently detect PD, the present investigation also revealed that these BIT/PZT sensors could be used for the estimation of the localization of a discharge source by the acquisition of the acoustic signal. The first experimental results are promising. Moreover, the tests have confirmed that this type of sensor can detect the electromagnetic signals emitted by the PDs. Therefore, it can be used in the location of PD foci.

Due to their inherent characteristics, this new technology of piezoceramic films provide an excellent economic alternative to be used in a real-time monitoring partial discharge system. Industrially speaking, we believe that mastering the various aspects of this technology will undoubtedly have a significant beneficial and innovative impact on preventive maintenance monitoring tools for electrical installations. Meanwhile, the application of this method to high voltage transformers can be considered relatively as recent. It still offers a

large field of research, in particular in the recognition of the pattern of discharges associated with the different types of defects, in the elimination of noise (signal denoising) and also in the development of efficient localization algorithms in the case of multiple nodes of discharges.

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