SPECIAL TESTS

Acoustic localization during Factory Acceptance Testing

Stefan Voeten

ABSTRACT

Factory Acceptance Testing (FAT) of power transformers includes the Induced Voltage Partial Discharge (IVPD) test, which ensures insulation integrity by identifying potential partial discharge (PD) sources. Internal PD sources can threaten long-term reliability and must be accurately located. Traditional electrical measurement techniques can narrow the PD location but lack the resolution for precise pinpointing. Acoustic localization, which detects the shockwaves emitted by PD events, offers a promising solution for this purpose. This article introduces a fiber-optic-based acoustic localization system capable of simultaneously reading up to 32 EMC-immune sensors. The approach enhances PD source detection and localization efficiency and reduces transformer inspection time. Two practical case studies illustrate the method's application and effectiveness in a production environment.

KEYWORDS:

Large power transformer, Partial Discharge (PD), Acoustic localization, Factory Acceptance Testing (FAT), Induced Voltage Partial Discharge (IVPD), EMC immune sensor

Induced Voltage Partial Discharge test is a part of the FAT, and its purpose is to stress the electrical insulation to reveal potential flaws in the insulation structure

Introduction

After the production of a power transformer is completed, it undergoes a series of rigorous assessments known as Factory Acceptance Testing (FAT). These tests verify that the transformer has been built according to design specifications, complies with relevant standards, and is free from manufacturing and material defects.

Among these assessments is the Induced Voltage Partial Discharge (IVPD) test, which stresses the electrical insulation to reveal potential flaws in the insulation structure. These flaws, when present, can result in localized electrical discharges that do not completely bridge the insulation between conductors, commonly referred to as partial discharges (PD).

A PD source can occur inside and outside the transformer. Examples of external PD sources are shown in Figure 1. A small metal part or an insect on the bushings can generate partial discharges. Another example of an external PD source would be a metal part on the transformer, which is not connected to a defined voltage, such as ground. One could think of a flange which is mechanically firmly mounted but due to, for instance, the paint layer, is not electrically connected to the transformer tank and thereby to ground. Such a metal part is referred to as a floating part. A floating part alters the electric field in its vicinity. If the electric field becomes too high, it can cause partial discharges.

Although these sources do not pose a risk to the quality of transformers, they do have to be removed to get a good measurement that verifies there are no internal PD sources.

Internal PD sources pose a significant risk for transformer long-term reliability because they can develop into a breakdown, causing a catastrophic failure. If an internal PD source is too strong, it must be removed. And here comes the

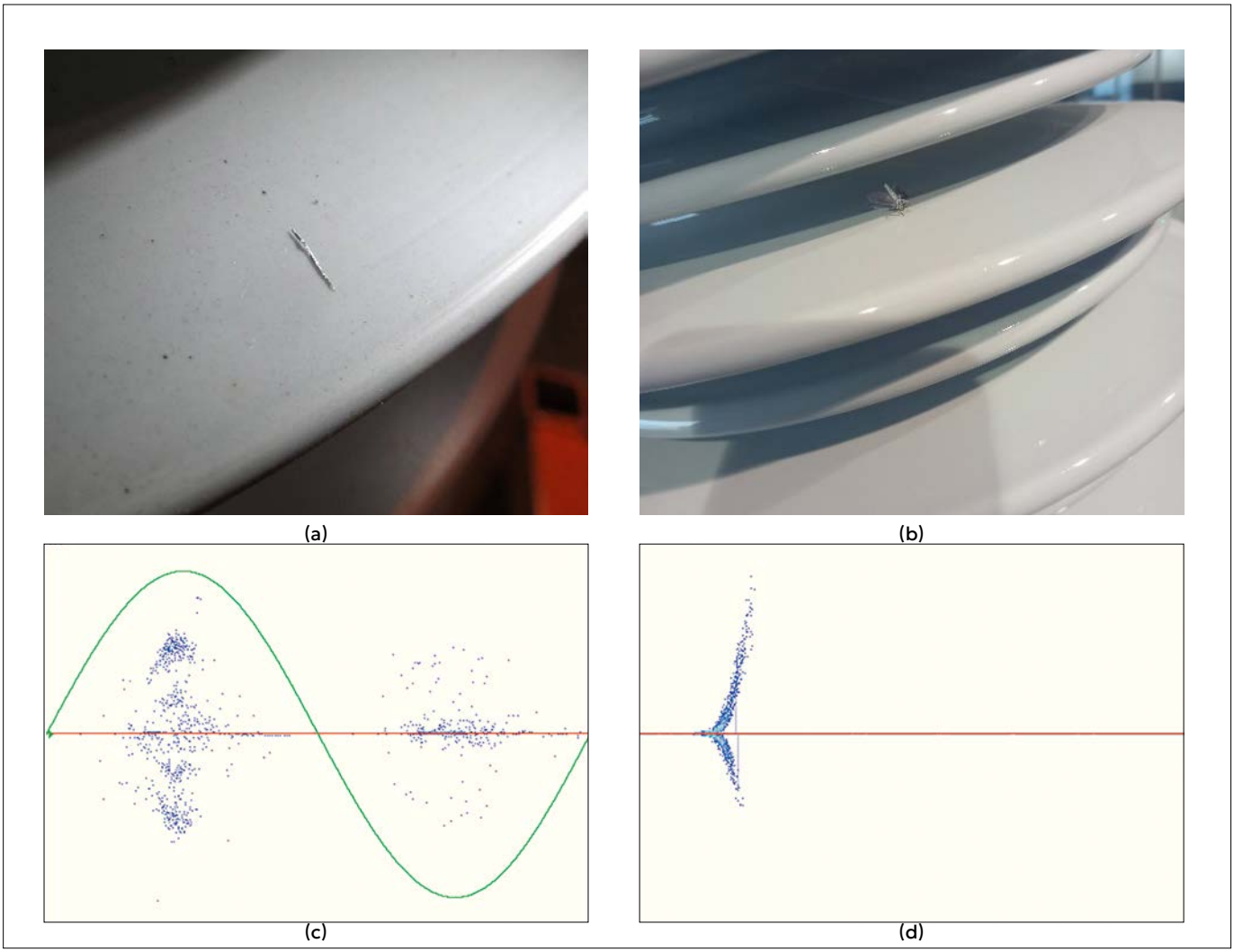


Figure 1. Examples of external partial discharge sources (a) and (c) small metal splinter on a silicone bushing, (b) and (d) a moth on a porcelain bushing

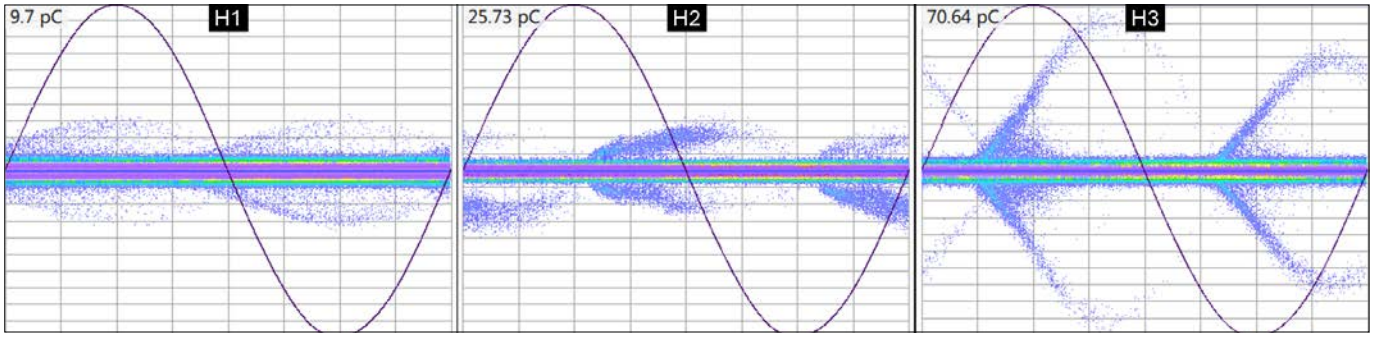


Figure 2. Example of recorded PRPD patterns, the amplitude at each phase readily gives an indication of which phase the PD source is located, in this case H3, as that phase has the largest amplitude

challenge: how to find something as small as a metal splinter in something as significant as a power transformer.

Conventional PD measurement systems, such as those using quadrupoles on bushing test taps (in accordance with standards like IEC 60270 and IEEE C57.113), can narrow down the suspected area. For example, analysis of the Phase-Resolved Partial Discharge (PRPD) pattern can indicate the most affected phase and whether the PD is nearer to the high or low voltage winding, as shown in Figure 2.

However, the measured PD levels are apparent charge levels, and their accuracy depends on the electrical impedance between the PD source and the measurement point. Additional measurements on tertiary windings, or on the core and clamping construction, may help refine the diagnosis. Still, these methods are limited in their ability to localize the PD source precisely. Not having a precise location to inspect the transformer increases the likelihood of not finding the PD source, which can thereby cause significant delays and costs.

A well-known method to pinpoint a PD source is acoustic localization [11]. This method is based on the fact that a PD source emits a small acoustic shockwave. If this shockwave can be detected, then the location of the PD source can be determined.

To make acoustic localization of partial discharges an accessible technique for a production environment, Royal SMIT Transformers [12] and OPTICS11 [13] have collaborated in recent years to simplify the measurement process.

Conventional PD measurement systems, such as those using quadrupoles on bushing test taps, can narrow down the suspected area, but cannot provide localization

The system described herein uses up to 32 fiber-optic-based acoustic sensors that are EMC-immune and capable of simultaneous, high-resolution measurements. This enables real-time and retrospective signal analysis and increases the likelihood of detecting even intermittent PD events. The system reduces the need for repositioning sensors and shortens overall test duration.

In this article, the basic principles of acoustic localization are described, and two practical examples are given.

Acoustic localization of PD source

Basic principle

A partial discharge causes high-frequency electric signals that can be picked up using quadrupoles at the test taps of bushings, as described in the IEC 60270 or IEEE C57.113.

Besides the electric emissions, a partial discharge also emits an acoustic shock wave. And it is this acoustic shockwave that can be used to localize the source of the partial discharge.

The localization of the PD source can be calculated using Time Difference of Arrival, TDOA, Eq. 1.

$$\sqrt{(X_{pd}-X_n)^2+(Y_{pd}-Y_n)^2+(Z_{pd}-Z_n)^2} = V_{oil}(T_{pd}-T_n)$$

With X_{pd}, Y_{pd} and Z_{pd} the X, Y and Z coordinates of the partial discharge source in meters, X_n, Y_n and Z_n the X, Y and Z coordinates of the n^{th} acoustic sensor in meters, V_{oil} the velocity of acoustic signals in meters per second, T_{pd} the time the partial discharge occurs in seconds, T_n the time the acoustic shockwave arrives at the n^{th} sensor.

Since there are 4 unknown parameters, X_{pd}, Y_{pd}, Z_{pd} and T_{pd}, the acoustics signal must be detected by at least four sensors. Solving such a set of equations is well described in the literature [3, 11].

A well-known method to pinpoint a PD source is acoustic localization, which is based on the fact that a PD source emits a small acoustic shockwave

The complex structure of the active part of the transformer and the different materials used cause the acoustic shockwave to be altered due to reflection, refraction, and attenuation

TDOA relies on the assumption that the recorded acoustic shockwave generates an accurate time of arrival, TOA, at each sensor. Therefore, the acoustic signal must have clear characteristics that identify the moment of arrival at the sensor.

But the complex structure of the active part of the transformer and the different materials used cause the acoustic shockwave to be altered due to reflection, refraction, and attenuation. As a result, the acoustic signal that arrives at the sensor is distorted, which complicates the determination of the actual TOA at each sensor.

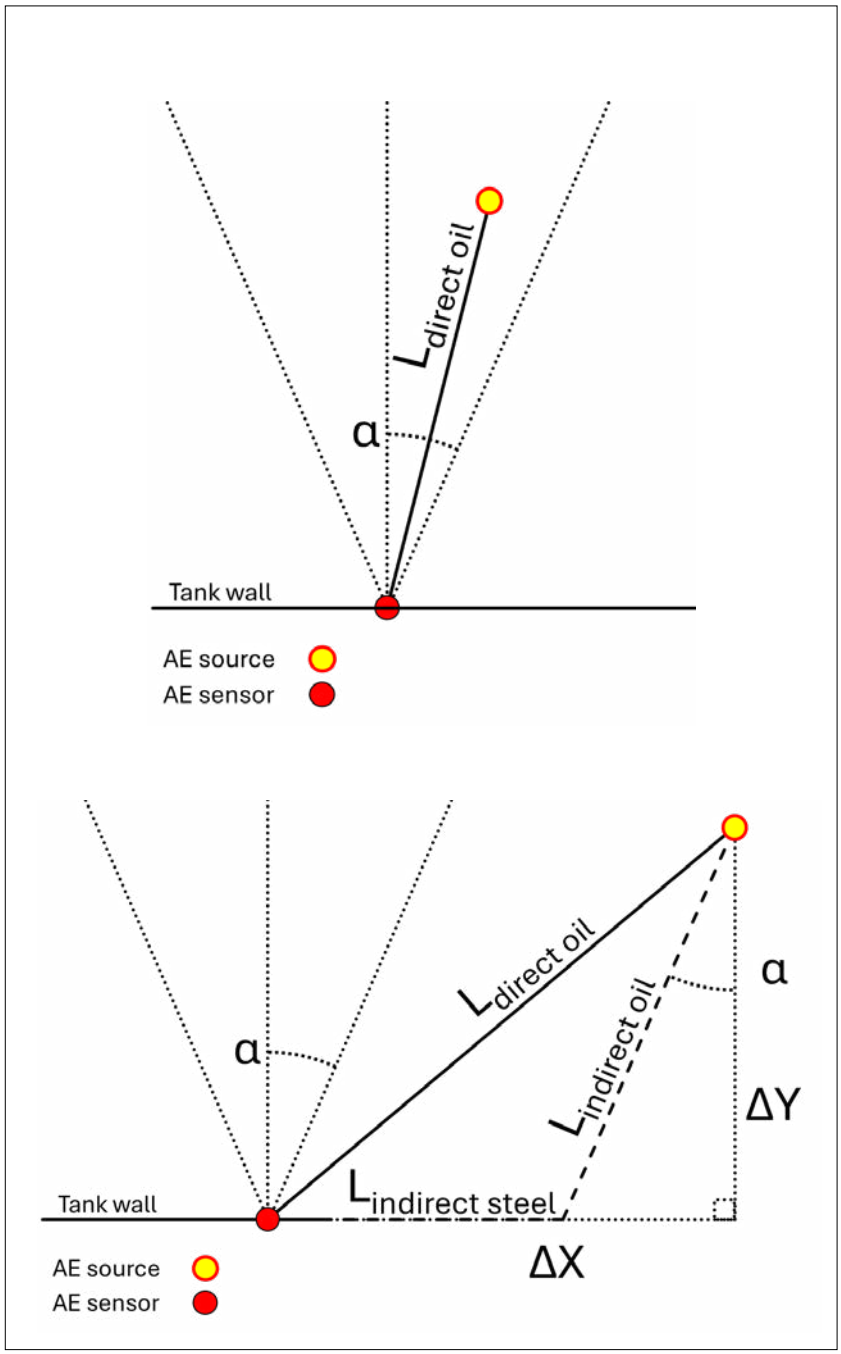


Figure 3. (a) An Acoustic Emission, AE, source, or PD source, in the direct field of view of the sensor will be detected through the direct oil path, (b) An AE source, or PD source, outside the direct field of view of the sensor will be detected through the indirect path

To overcome this, one can look at the energy in the acoustic signal. The moment the energy in the signal is at its minimum coincides with the TOA, Eq. 2 and Eq. 3, [6].

$$S = \sum_{i=1}^{n} x^2(i) - n\frac{s_N}{N} \qquad \text{Eq. 2}$$

$$s_N = \sum_{i=1}^{N} x^2(i) \qquad \text{Eq. 3}$$

Here s_N is the total energy of the signal, S the signal energy, n the number of samples up to which the energy is calculated, N total number of data points, and $x(i)$ the value at each data point.

Sensor field of view

Another important aspect to take into account during acoustic localization is the field of view of the acoustic sensors. Acoustic sensors placed on the wall of the transformer tank have a field of view limited by the ratio of the velocity of acoustic signals through oil to that through steel. Depending on the temperature and oil type, the velocity of acoustic signals through oil varies from below 1250 m/s for temperatures above 65ºC, to over 1450 m/s for temperatures below 20ºC [4]. In steel, acoustic signals propagate much faster and can travel transversally and longitudinally at different velocities. These velocities depend on material properties.

A study on the effect of the field of view of the sensor on the acoustic shockwave as recorded by the acoustic sensors is done in [1].

The ratio between the velocity in oil and through steel results in an angle that defines the area within which the sensor will detect the acoustic signal directly through oil or outside, where the sensor will detect the acoustic signal through the tank wall first (Figure 3). For a velocity in oil of 1400 m/s and a transversal

When the sensor picks up the acoustic signal through the tank wall before it receives the signal directly through oil, the recorded acoustic signal no longer represents the TOA through oil

velocity through steel of 3500 m/s, an angle α of 23.6º is obtained.

$$\alpha = \arcsin\left(\frac{v_{oil}}{v_{steel}}\right) = \arcsin\left(\frac{1400\ m/s}{3500\ m/s}\right) = 23.6° \quad \text{Eq. 4}$$

When the sensor picks up the acoustic signal through the tank wall before it receives the signal directly through oil, the recorded acoustic signal no longer represents the TOA through oil, and as such, an error is introduced when applying Eq. 1.

Shown in Figure 4 is the test setup used to identify the sensor response to a PD source detected through a direct and indirect path [1]. A piezo element, used to mimic a PD source, is placed at the center of the tank. An array of 15 acoustic sensors is placed on the side of the tank. Figure 4(b) shows the top view of the tank, showing the 5 sensors in the middle horizontal line. Sensor S3 has the PD source in its field of view. All the other sensors will pick up the acoustic signal through the steel wall of the tank first.

The acoustic shockwave as recorded by the 5 sensors is shown in Figure 5.

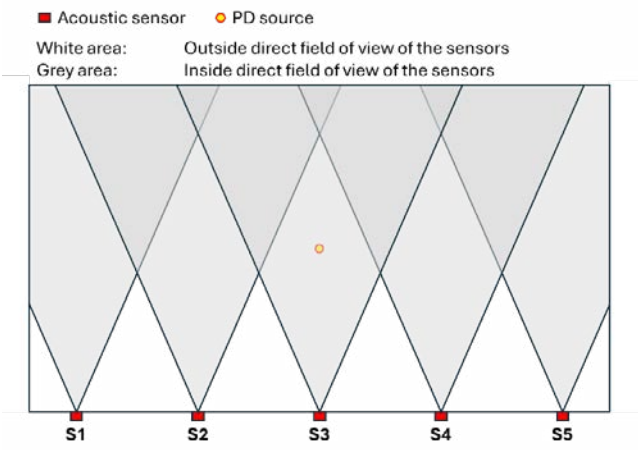


Figure 4. (a) Test setup with a tank filled with only oil, (b) schematic top view, only the center sensor, S3, has the PD source in its direct field of view

With an unknown PD source location, the acoustic signals must be analyzed carefully to distinguish between directly and indirectly detected acoustic signals

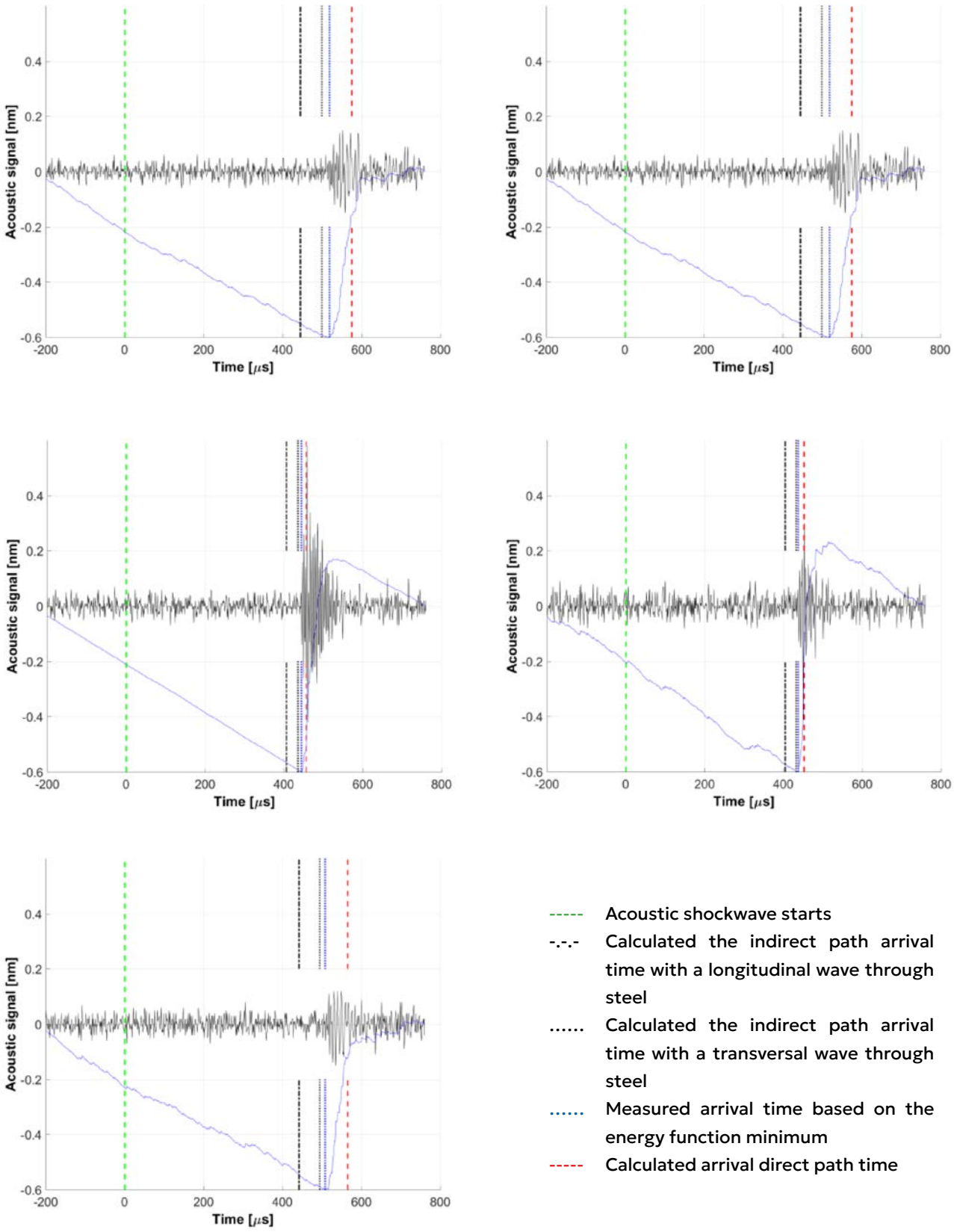


Figure 5. (a) Sensor S1 response, (b) Sensor S2 response, (c) Sensor S3 response, (d) Sensor S4 response, (e) Sensor S5 response

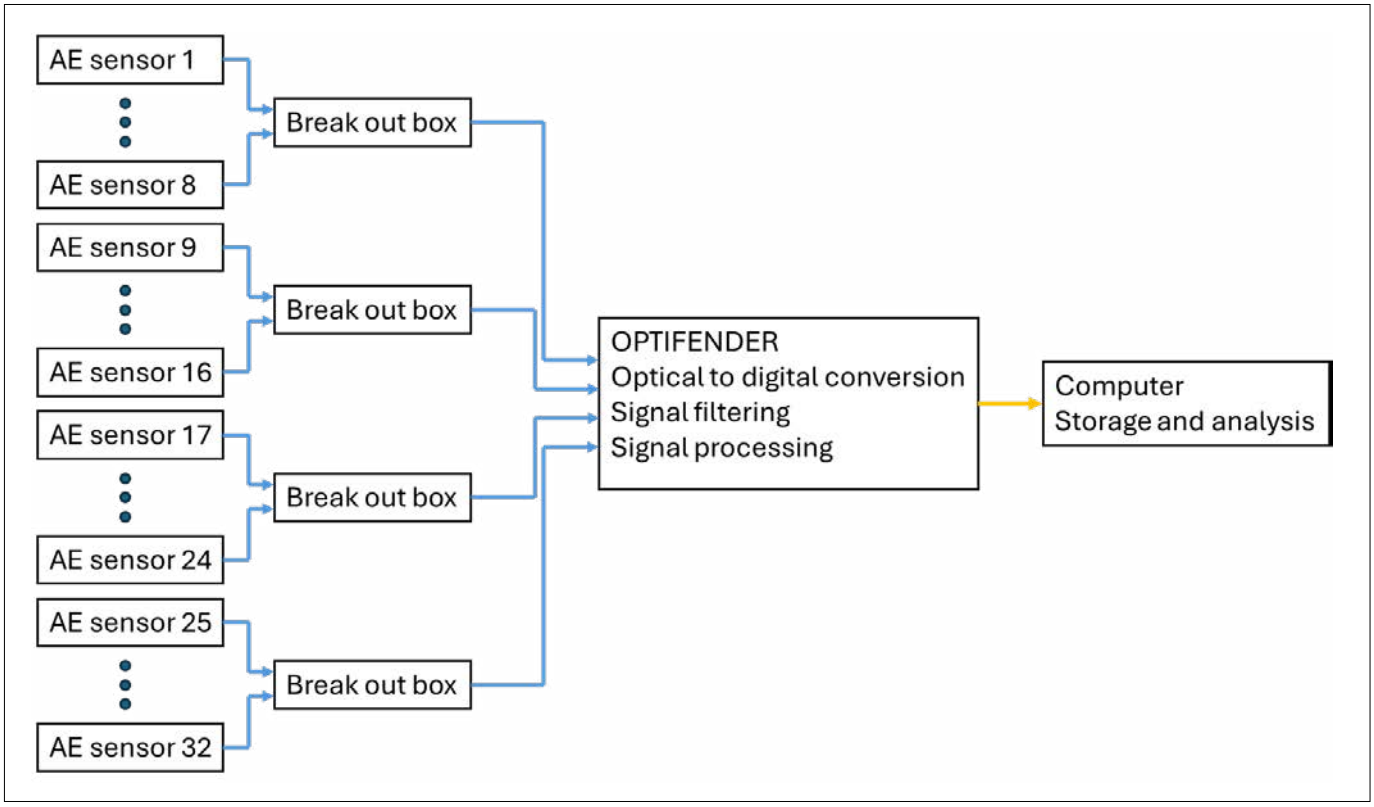


Figure 6. Schematic representation of the acoustic sensing system

During the Induced Voltage Partial Discharge test on a 3-phase autotransformer, rated at 560 MVA and 345 kV to 120 kV, a large PD signal was detected

The sensor in the center, S3, has the PD source in its direct field of view, and as a result, it has a very clear signal, Figure 5(c). The minimum of its energy function, blue graph, indeed coincides with the front of the acoustic wave and with the calculated TOA, vertical red dashed line.

For sensors S2 and S4, in Figure 5(b) and (d), it can be seen that the minimum of the energy function is slightly before the calculated TOA, and it matches closely to the calculated TOA through the indirect path, vertical black dotted line.

For the two outermost sensors, Figure 5(a) and (e), the minimum of the energy function appears after the calculated TOA through the indirect path.

With an unknown PD source location, the acoustic signals must be analyzed carefully to distinguish between directly and indirectly detected acoustic signals. An indirectly detected acoustic signal will introduce an error in the determination of the partial discharge source location.

In the following section 2 practical cases of PD source localization are described. The approach taken in these cases is to, solely based on the detected acoustic signals, generate a 3D map of all calculated locations. The point where the density of calculated locations is highest is the most likely location of the PD source.

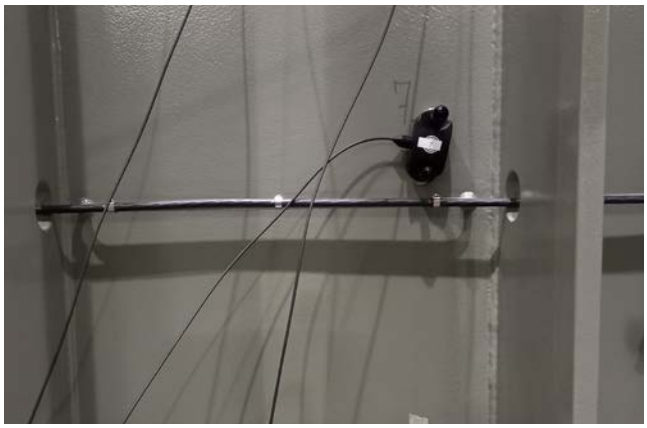
Practical cases of acoustic localization

Setup

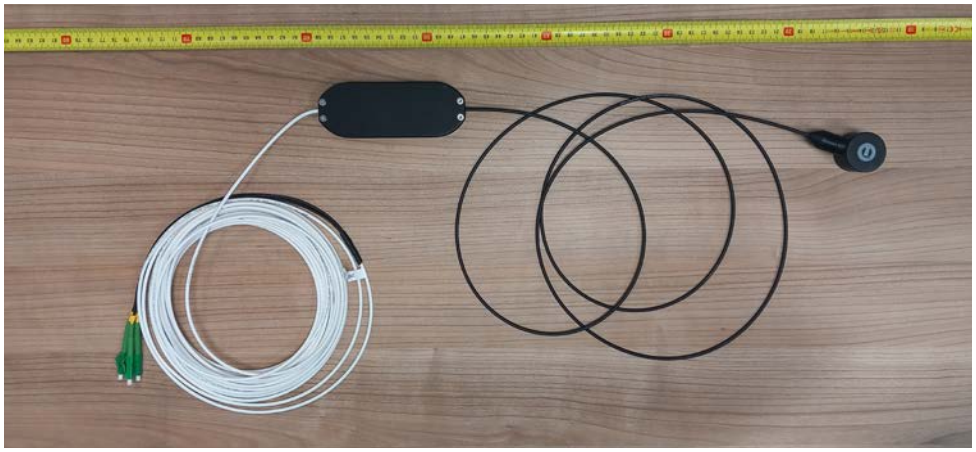
A schematic representation of the complete acoustic system is shown in Figure 6. Up to 32 acoustic sensors can be placed on the transformer using magnetic clamps, Figure 7 (b). The fiber optic cables of the sensors are grouped in groups of eight sensors in so-called break out boxes, Figure 7 (d), into multifiber cables, which then are routed to the Optifender, Figure 7 (e). Here, the fiber optic signals are converted to digital signals, filtered, and sent to the computer for storage and analysis. The advantage of this setup is that in the high-voltage test bay, there is only passive fiber optic equipment. All the electronics are outside the high-voltage test area. This makes the system ideal for the test environment of large power transformers, as it is inherently insensitive to EMC and large currents.

The acoustic localization has drastically reduced the area that was to be inspected, resulting in a reduction of inspection and repair time and cost

(a)



(b)



(c)

(d)

(e)

Figure 7. (a) The passive fiberoptic acoustic sensor, (b) mounting of the sensor on the transformer tank wall with a magnetic clamp, (c) the sensitive sensor head at the left, reference sensor in the middle and fiber optic lead that goes to the break out box, (d) breakout box, here the fiber optic cable of up to eight sensors are combined into a multifiber cable, (e) The Optifender that digitizes the optical signals from the sensors, filters and processes them and sends the signals to the computer for storage and analysis

Case 1: Internal floating part

During the Induced Voltage Partial Discharge test on a 3-phase autotransformer, rated at 560 MVA and 345 kV to 120 kV, a large PD signal was detected, as shown in Figure 8(a). Based on the quadrupole signals, the PD source was found to be somewhere on the low voltage center phase X2, Figure 8 (b). For acoustic localization, eight sensors are placed on the low-voltage side of the center phase, as indicated by the red encircled yellow dots in Figure 8(d).

The calculated locations based on the acoustic signals are shown with colored dots in the top, front, and side views in Figure 8(b) through (d). The color of the dots ranges from blue to yellow and represents a measure of likelihood; the more yellow the color, the more likely the source is at that location.

Figure 9 (a) shows an acoustic signal originating from the direct field of view of the acoustic sensors, and Figure 9 (b) shows an acoustic signal originating from outside of the direct field of view of the acoustic sensors.

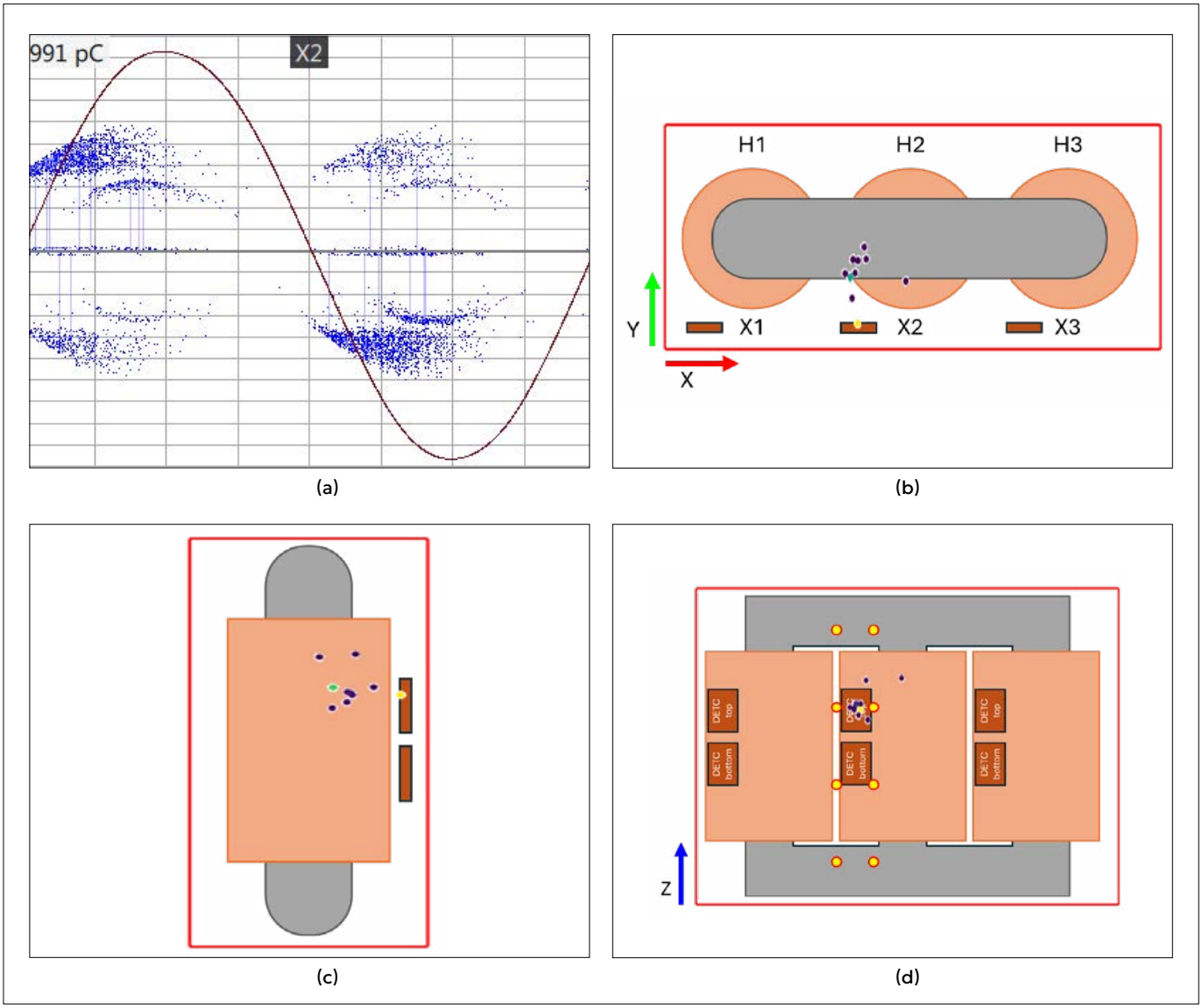


Figure 8. (a) PRPD pattern as measured on the X2 bushing tap, (b) PD location as seen from the top, (c) front, (d) side. Dark brown parts indicate the location of the DETC. Sensor locations indicated with red-encircled yellow dots, Colored dots indicate calculated locations

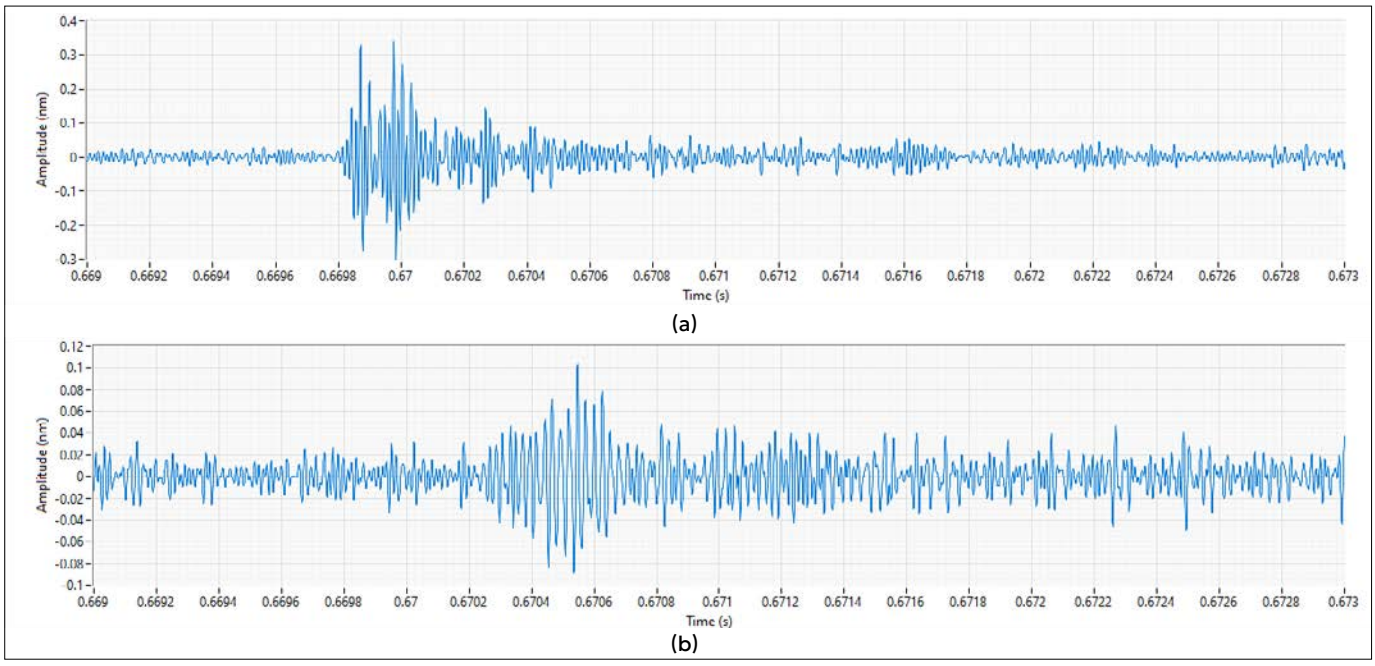


Figure 9. (a) Acoustic signal in the direct field of view of the acoustic sensor; steep rising edge, (b) acoustic signal not in the direct field of view of the acoustic sensor; gently rising edge

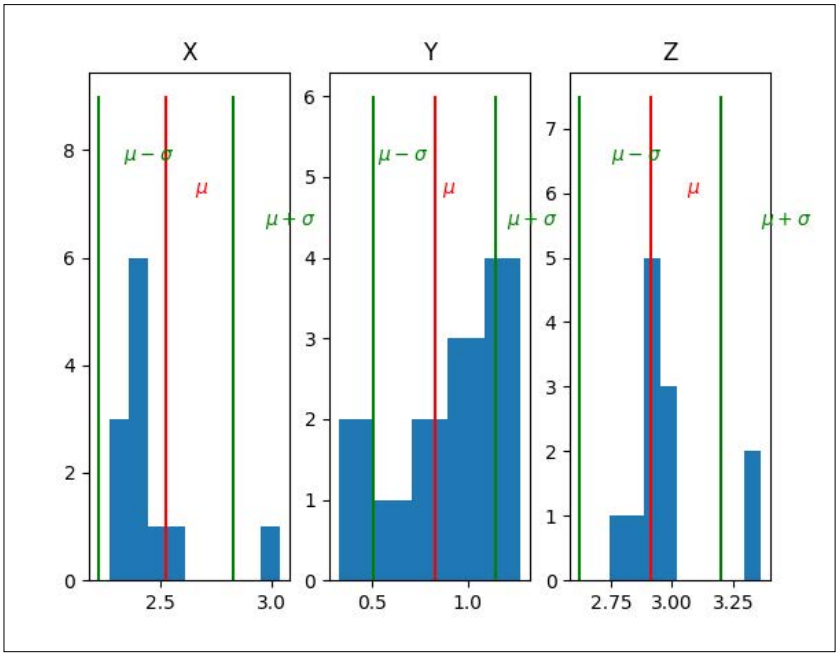


Figure 10. The vertical axis shows the number of 'hits' at a location. The horizontal axis of the left graph is the X axis, the long side of the transformer. The middle and right graphs have the Y and Z axes of the transformer on their respective horizontal axis. The higher the count, the more likely the PD source is at that location. In the heatmap, this is indicated with a more yellow color.

During the Induced Voltage Partial Discharge test on a 3-phase autotransformer, YNd5 560 MVA, 275 kV to 66 kV, a partial discharge was detected with the quadrupole on the test-tap of the H3 bushing

Figure 10 shows the statistics of the locations' calculations. The left graph shows the counts of locations with respect to the transformer x-axis, as defined in Figure 8(b). The center and right graphs show the counts, but then for the y and z-axis, respectively. Since a few PD signals lead to successful location determination, the statistics in this case are very coarse, and little additional information can be drawn from them.

Upon closer examination of the calculated locations, many of them are situated deeper than expected within the transformer. This is mainly due to the fact that all sensors are placed on the same side of the transformer. As a result, the determination of the location becomes less accurate in the direction perpendicular to this plane.

During inspection, an ungrounded electric shield of a bolt on the DETC at the indicated location was found to be the cause, validating the results obtained from the acoustic localization. The acoustic localization has drastically reduced the area that was to be inspected, resulting in a reduction of inspection and repair time and cost.

Case 2

During the Induced Voltage Partial Discharge test on a 3-phase autotransformer, YNd5 560 MVA, 275 kV to 66 kV, a partial discharge was detected with the quadrupole on the test-tap of the H3 bushing, shown in Figure 11(a). For the localization, the acoustic sensors were placed as shown in Figures 11(c) and (d).

Having the sensors on two sides results in good localization in all three directions.

In this case, the number of calculated locations was much larger (Figure 12). These statistics indicate that the results can be interpreted as very reliable. During inspection, the PD source was indeed found at the high voltage exit lead, at the indicated location.

Conclusion

Accurate localization of PD sources is of key importance when partial discharges occur in a transformer during FAT. The presented setup, based around the OPTICS11 Optifender, using multiple acoustic sensors, has shown the capability to reliably and accurately locate PD sources solely based on the acoustic sensor signals.

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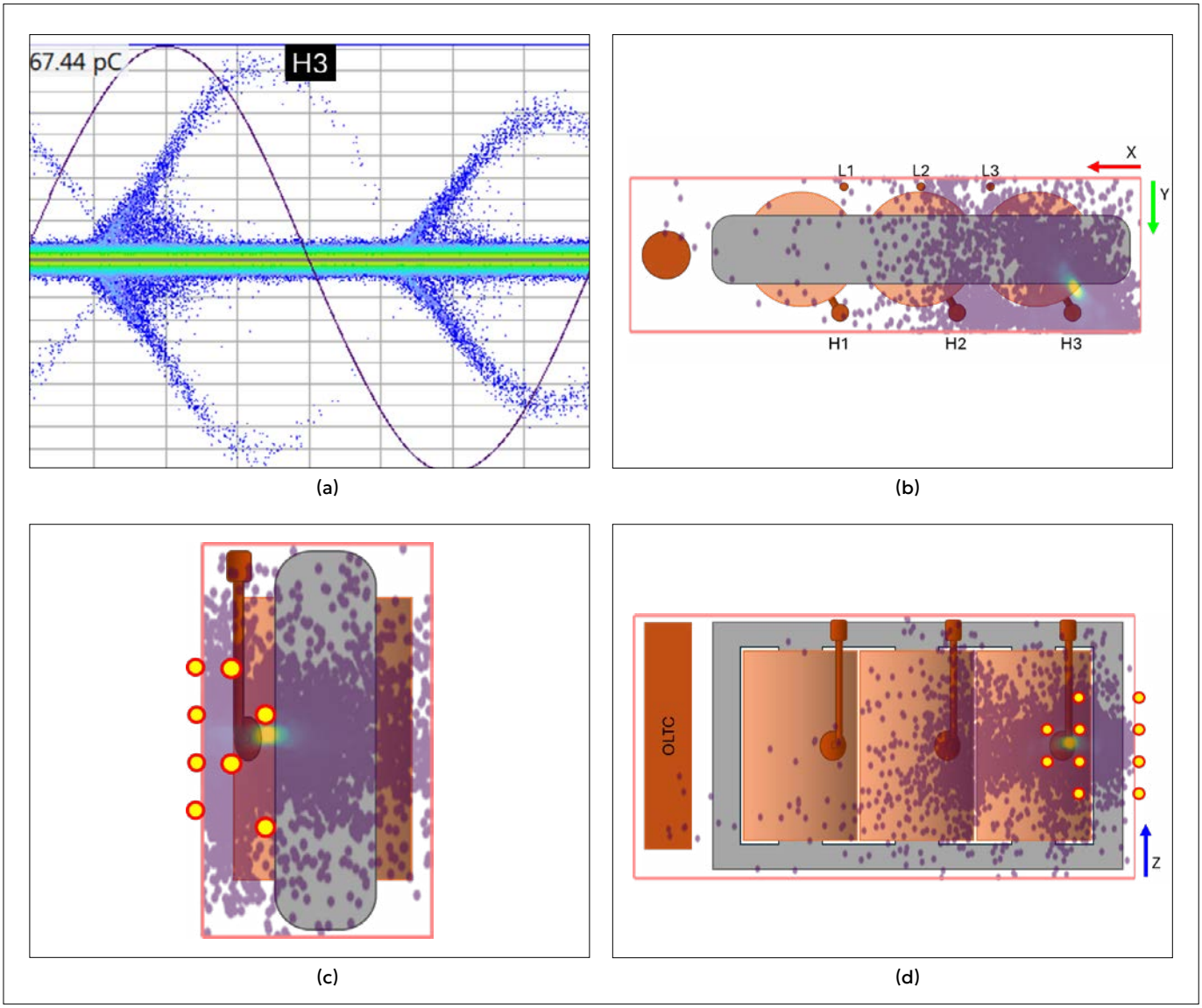

Figure 11. (a) PRPD pattern as measured on the H3 bushing tap, (b) PD location as seen from the top, (c) front, (d) HV side. Dark brown parts indicate the HV lead exit. Sensor locations indicated with red-encircled yellow dots, Colored dots indicate calculated locations

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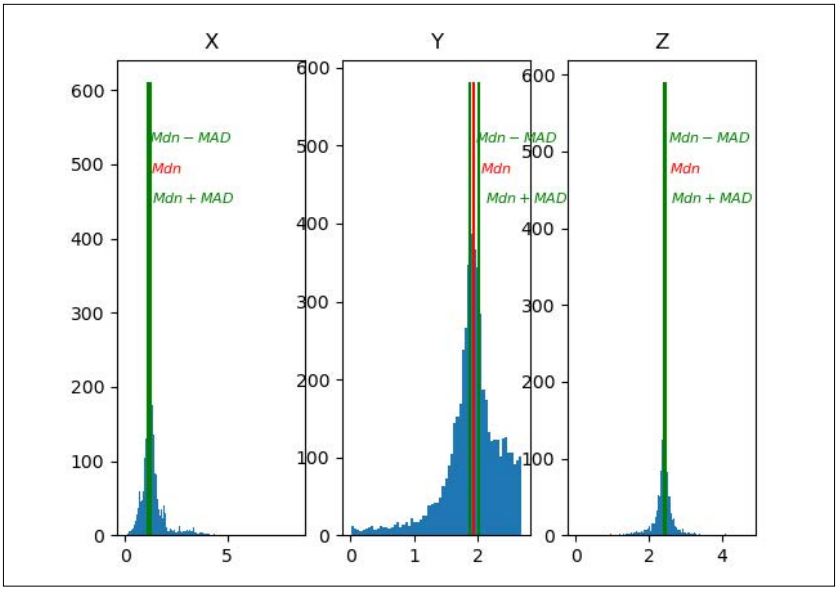

Figure 12. The Vertical axis shows the number of 'hits' at a location. The horizontal axis of the left graph is the X axis, the long side, of the transformer. The middle and right graphs have the Y and Z axes of the transformer on their respective horizontal axis. The higher the count, the more likely the PD source is at that location. In the heatmap, this is indicated with a more yellow color.

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