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On-site Partial Discharge Testing of Transformers

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SUMMARY

Partial discharge activity is one of the first precursors to insulation deterioration or design related issues that if left to manifest can lead to a breakdown in the insulation system, potentially resulting in unplanned outages, costly repairs, and even replacement of high voltage equipment. Performing PD measurements offers the advantage to indicate a problem, but also to reliably locate the issue within the transformer by a triangulation process with acoustic sensors. Also, the phase-resolved partial discharge (PRPD) pattern is displayed on the PD detection instrument for analysis. The appearance of the PRPD patterns is indicative of the type of defect together with the position and the materials involved.

Measured signals are affected by reflections, cross-coupling, and attenuation effects on the travel path from the origin of the PD activity to the measuring terminals. Proper analysis of the influence of these effects on the measured signals also adds valuable information about the origin of PD activity inside a transformer. Therefore, PD testing is a well-established diagnosis method for shop floor testing and also part of the factory acceptance tests for power transformers.

PD testing can be applied to more than just shop-floor and factory acceptance testing, it is also possible to perform PD measurements and fault research under on-site conditions. This allows for testing during planned outages in which issues can be identified, located, and repaired before resulting in breakdown during operation. Also, once PD activity has been detected in a transformer, acoustic sensors can be utilized to determine the location of the defect.

This paper will discuss on-site partial discharge detection methods for transformers. It will highlight the obstacles faced during on-site measurements compared to shop-floor testing and provide techniques used to confront them. Additionally, this paper will cover the analysis of the signal transmission effects, interpretation techniques for PRPD patterns of typical transformer defects, and techniques for localization of PD within a transformer using acoustic sensors strategically placed on the transformer tank.

KEYWORDS

Partial Discharge, Background Noise, On-site Testing, Transformer, Diagnostics, Acoustic Measurements, Insulation System, Phased Resolved Partial Discharge (PRPD)

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Introduction

There are several methods of testing and diagnostics for transformers that provide insight into their condition. While some of these tests are more common, such as turns ratio, winding resistance, and power factor, there are advanced diagnostic methods used to determine a transformer's insulation condition such as Dissolved Gas Analysis (DGA). While DGA testing has the ability to identify issues or defects in transformer systems, some of these gases are a result of partial discharges and often times lead to an indication that PD testing should be performed. Partial Discharge testing allows for the ability to identify defects in a transformer at an earlier stage and therefore allow for more appropriate decisions to be made for its correction. As a transformer's insulation system ages, the dielectric strength begins to decline. This process leaves the insulation system subject to partial discharges due to weak spots or regions. Localized defects can also be the cause of partial discharges in new or in aged insulation systems by creating electric field enhancements that can exceed the insulation's dielectric strength.

Partial Discharge can manifest within a transformer in many ways, potentially causing severe damage over time or sometimes result in catastrophic failures. Some examples of PD sources in transformers can be sharp points, surface discharge, fiber bridges in oil, voids, and delaminations. The graphic below, provided by CIGRE, contains the statistics for failure location of generation step-up transformers rated greater than 100 kV taken from 127 major failures [1]. This is a clear illustration of the number of different ways that transformers can experience major failures and the importance of performing asset condition assessments.

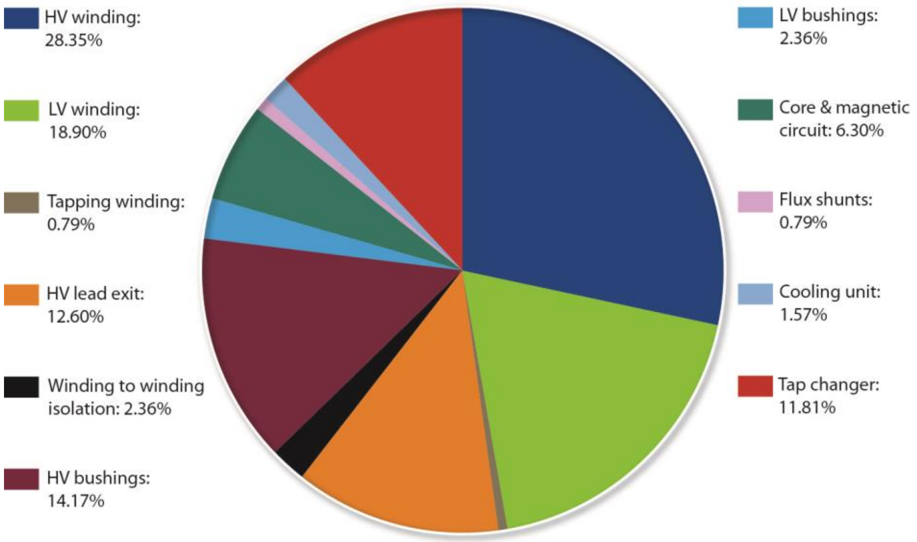

Figure 1: Failure location statistics for generation step-up transformers (>100kV) based on information from 127 major failures [1].

Partial Discharge in Transformers

Transformers are intricate systems with complex designs comprised of several components such as insulation barriers and spacers made of cellulose, a core made of ferromagnetic material, windings that are typically made of aluminum or copper, and different types of insulating oils. When PD is present in a transformer, each discharge generates different measurable signals such as local displacement current pulses, electromagnetic pulses, and acoustic pulses. Figure 2 contains examples of these three types of measurements taken from transformers. The first, on the left, is an example of an electric PD pulse measurement taken from a bushing tap. The middle figure contains an Ultra High Frequency (UHF) measurement from an antenna inserted into a transformer's oil valve. Then the third example, seen in the right figure, is an acoustic measurement from sensors placed on the transformer's tank wall.

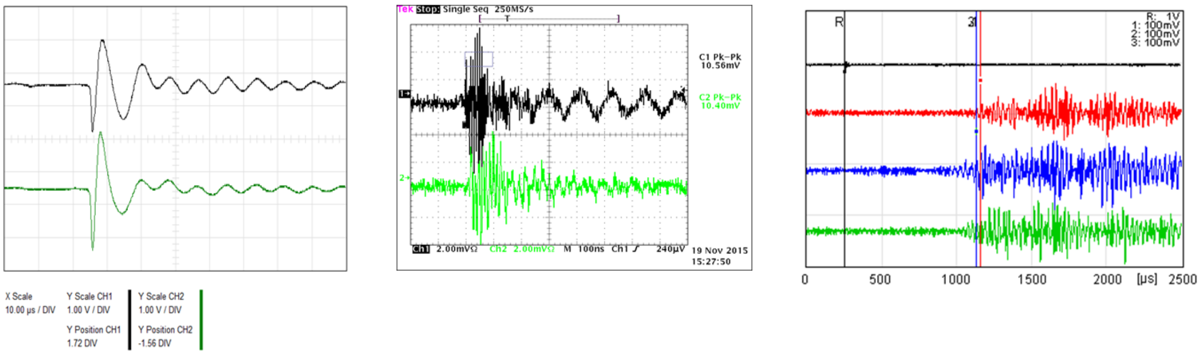

Figure 2: Examples of PD measurement techniques that can be applied to transformers.

The complex design of a transformer, mentioned previously, affects the signal propagation from partial discharges with reflections, cross-coupling, and attenuation, but this also allows for additional insight into the defect type and possibly provide a general idea of where the defect could be. This is typically done through the analysis of Phase Resolved Partial Discharge (PRPD), or φ-q-n, patterns. A PRPD pattern is a three-dimensional figure generated by plotting the measured PD activity, where the X-axis represents the phase angle of the applied voltage, the Y-axis represents the magnitude of discharge, and the color of the pattern indicates the number of discharges. For instance, Figure 3 contains two examples of void discharges in a transformer. The figure on the left has the distinct signature shape of a void discharge in the insulation, where the pattern tends to follow the shape of the applied sine wave. As previously mentioned, the location of the discharge in a transformer and the availability of a free electron to start the process can also have an effect on the pattern. The PRPD pattern to the right in Figure 3 is also of a void discharge, but with a high availability of starting electrons. This is indicated by the number of discharges in a more concentrated area than in the measurement shown on the left.

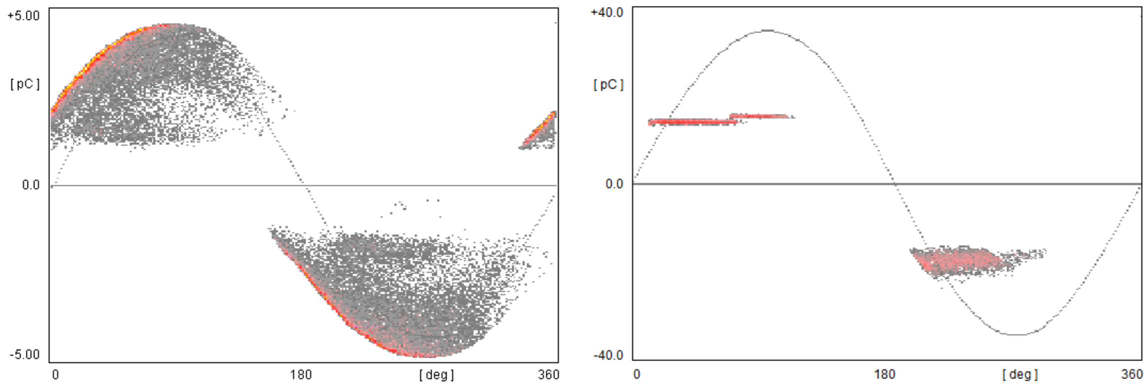

Figure 3: PRPD, or φ-q-n, patterns for voids in the insulation.

Another example of PRPD analysis is comparing measurements to identify cross-coupled signals and determine the originating phase. Typically, the amplitude of discharge is sufficient enough to estimate the originating phase. However, PD activity deep in the winding can result in cross-coupling with other phases and show discharges with similar amplitudes. In this situation, comparing the PRPD pattern for different phases can reveal valuable information and lead to identifying the originating phase. Figure 4 contains three PRPD patterns with the indication of two void discharges. The figure on the top left is the result of a PD measurement taken on one phase, but it is evident that the void discharges do not align with the applied voltage, indicating that this is likely a cross-coupled signal. The PRPD pattern on the top right is the result of a PD measurement on another phase and now the void discharges align with the applied voltage, indicating that this is the originating phase. The amplitude of discharges is very similar on both phases, which lead to a measurement on the neutral as seen in the bottom figure. The signal is significantly stronger on the neutral, which further confirms that the discharge activity must be taking place deep within the winding on the originating phase.

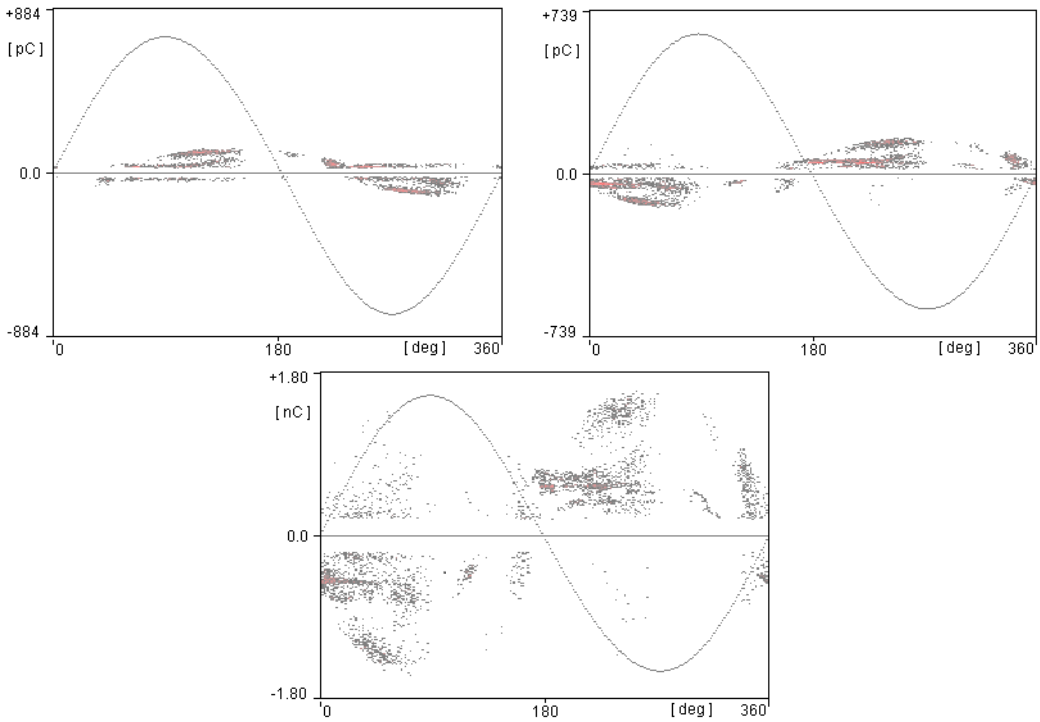

Figure 4: PRPD pattern comparison to determine the originating phase and provide insight into the location of discharge activity.

On-site Transformer PD Testing

A comparison cannot be made between factory acceptance testing (FAT) in a shielded room that has been optimized for PD testing and on-site testing, which is often in a noise polluted environment. Both on-site and factory testing may be done using different techniques, but the measurements must be performed in accordance with respecting standards, such as IEC60270 and IEEE standards C57.12.00, C57.12.90, C57.19.00, and C57.113[2,3,4,5,6]. On-site testing of transformers is a demanding task and takes proper preparation before the measurement can be performed. The first task at hand is the installation of the mobile test system, typically either an inverter based three-phase system or a large motor generator system. Once the mobile test system has been installed, the transformer must be isolated from the grid and installed with electrodes to prevent corona discharge from interfering with the measurement in the event that the transformer has open air bushings. Figure 5 contains a photograph of corona shields mounted on 500 kV open air bushings with a PD free connection to a 500 kV resonance reactor during an on-site applied voltage test.

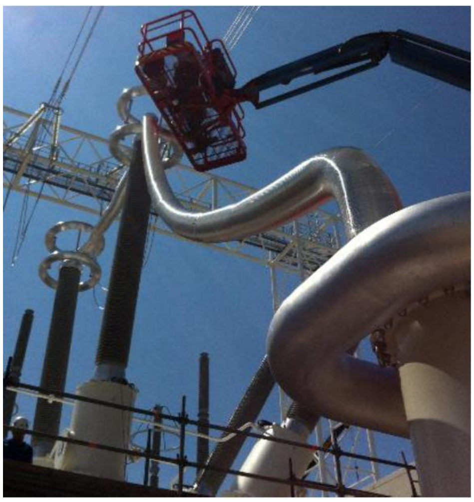
Fig. 5: Mounting of corona shielding and PD free HV line.

When performing an induced AC voltage test, the voltage is typically applied to the low voltage (LV) bushings of the transformer using shielded cables. When performing a three-phase induced voltage test, the step-up transformer of an inverter based three-phase system can operate by setting the phase shift of the inverters to 120° [7]. To perform a single-phase induced test, the phase shift of the three-phase inverters can be set to 0°, allowing full power at the step-up transformer. It is always important to keep in mind the reason for testing, for instance, the test voltages used after a repair or recommissioning are likely going to deviate from those specified by the standards when testing new transformers. Section 8 of the IEC 60076-3 states that any transformer that is repaired to restore its functionality but is still to be regarded as compliant with this standard shall be subject to the tests described in this standard necessary to verify the repair at a test voltage of between 80 % and 100 % of the original test voltage level [8].

The induced voltage test is intended to determine the phase-to-ground and the inter-phase withstand strength of the terminals and the winding insulation. In regards to both IEC and IEEE standards, in addition to induced voltage tests, and typically prior to, an AC withstand voltage test is part of routine acceptance testing [3,4,8]. The main purpose of these tests are to determine the condition of the winding-to-ground insulation and do not require that the transformer be energized. Also, as opposed to the induced voltage, the applied voltage test can be performed at +/ 20 % of the rated frequency. Typically, in factories, this is done by using large resonant test systems to reach the required test voltage. An example of an AC mobile test system, capable of performing applied voltage tests up to 500 kV using a series resonance inductor, for on-site acceptance testing can be seen in Figure 6.

Figure 6: Inverter based three-phase mobile test system for on-site testing.

Performing PD testing during an applied voltage test is not considered a routine test, but can offer a better understanding if the need arises to perform troubleshooting on winding-to-ground problems or issues in the barriers between HV and LV windings. To perform PD testing together with an applied voltage test, a PD free connection, as seen in Figure 5, must be installed between the mobile test system's reactor and the transformer's bushing. An alternative in the field could be transformers with shielded HV cable terminations or oil cable boxes, in which specific PD free test adapters may be required.

The most critical parameter during a partial discharge test, regardless of the setting, is the level of noise. One aspect to help achieve a low level of noise is to apply a clean sine wave when testing. Appropriate filtering is required to avoid high frequency disturbances coupling into the measurement circuit from the HV supply used. Mobile test systems that utilize motor generator systems in combination with step-up transformers are subject to switching pulses from the rectifier or from brush noise that can affect the quality of measurement. With inverter based systems, like the one seen in

Figure 6, the importance lies with the control and suppression of IGBT switching noise by using the appropriate filtering. In these systems, the filtering is applied after the inverter on the LV side and then at the HV side of the step-up transformer. The high-pass filter of the PD acquisition system should remove any residual noise from the source that made it past the filtering. Additionally, noise from switching can be removed from the measurement using the gating function of the PD detector being used.

With the noise from the power source eliminated, the ambient background noise can be measured. A background noise level below 10 pC is achievable when testing in a shielded room, but when testing in a substation environment, the background noise can be well above 100 pC when adhering to the IEC60270 frequency band. The transformer tank typically provides shielding for the winding, but open air bushings can act as antennas and impact the measurement. A spectrum analysis can be performed to gain more information in regards to the background noise and the signal-to-noise ratio (SNR). Figure 7 contains an example of a typical transformer spectrum analysis, where the blue trace represents the calibrator pulse and the red trace represents the ambient noise.

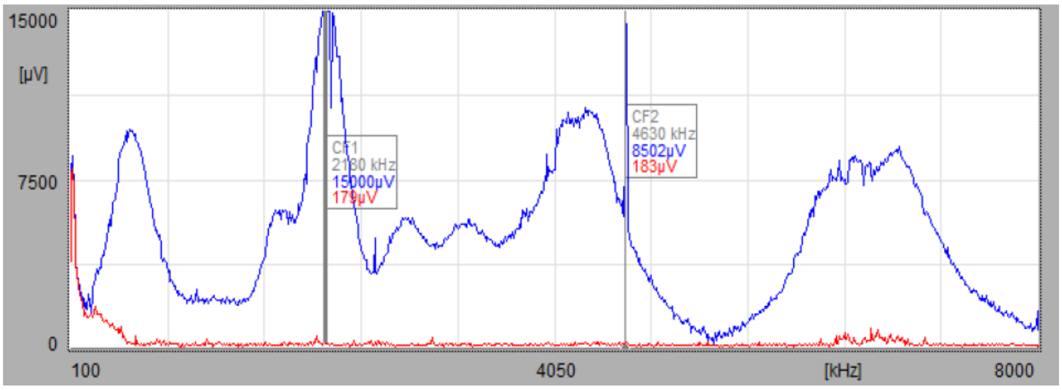

Figure 7: Typical spectrum analysis for transformers providing a visual of the SNR.

Utilizing the spectrum analysis, an appropriate frequency band can be chosen to provide a sufficient SNR as seen in the figure above. Using the spectrum analysis and noise eliminating techniques will allow for optimal measurements during the PD testing. When eliminating noise, the first step is to validate if and where the noise is being coupled into the measurement circuit. Next, would be to utilize the applicable noise eliminating tools such as noise gating features, line and ground filters, spectrum analyzer, and software controlled filters. Utilizing these techniques help make it possible to achieve background noise levels to the <50 pC limit for oil-filled power and distribution transformers and to <100 pC for current limiting reactors. However, when performing an on-site AC acceptance test on dry type distribution transformers, achieving noise levels <10 pC becomes very difficult, even when applying all possible noise elimination techniques and filtering.

Acoustic Location

As previously mentioned, PD activity generates several different measurable signals that can be used for detection and localization of the PD source. Acoustic signals, generated by the PD pulses, are used along with the travel times through different materials to determine the location of the PD source. Transformers are comprised of several different materials, each with their own density, affecting the travel speeds of acoustic signals as they travel through the tank. Therefore, if the PD activity is deep within the insulation system there are various signal transmission paths. Additionally, the attenuation, reflections, and delays all lead to increased difficulty in locating the source of PD. The transformer tank wall also has its own transmission properties and adds an additional signal path. For these reasons, the textbook triangulation approach of 3 sensors, each placed on different faces of the tank wall, is typically not a viable option. Instead, the problem can be reduced from a three-dimensional to two-dimensional solution by placing several acoustic sensors in close proximity and performing the measurement with the sensors first placed horizontally and then vertically.

An in-depth PD diagnosis and analysis should be performed before attempting an acoustic location on transformers to gain a rough location of the PD source. Based on the results of the diagnosis and analysis, several acoustic sensors can be placed on the tank wall, as seen in Figure 8, near the suspected area to measure acoustic signals in relation to the PD signal.

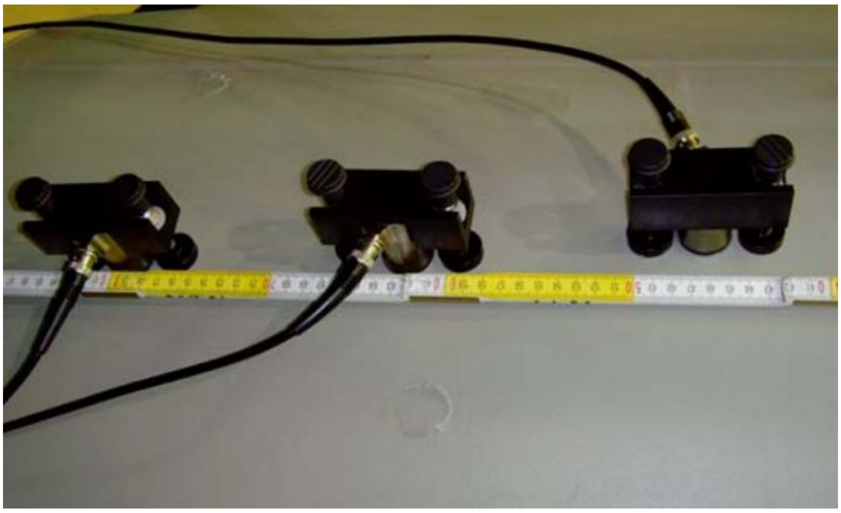

Figure 8: Acoustic sensors fitted to the tank wall using magnets to determine the location of PD source.

To measure the electrical and acoustic signals an oscilloscope is set to trigger on the dominant electrical signal, while displaying the averaged acoustic signals measured by the piezoelectric sensors placed on the tank wall. Figure 9 contains a screenshot from an oscilloscope with such signals with different travel times depending on the sensor positions.

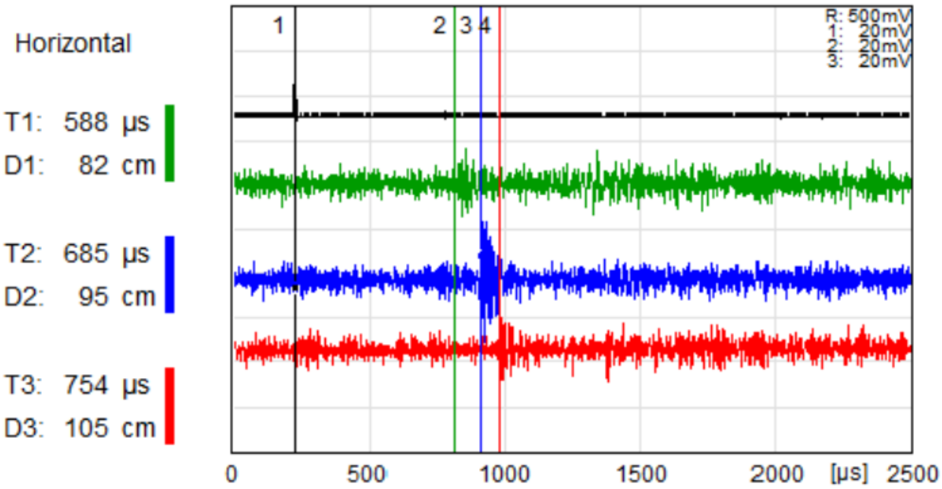

Figure 9: Oscilloscope screenshot containing the trigger on electrical signal and corresponding acoustic signals with different travel times.

When placing the sensors on the transformer tank, it is ideal to position them to have a simple signal path, such as a clear oil path, to avoid the signal effects due to the complex insulation system. It is essential to have the internal schematics of the transformer when performing acoustic PD location. Once an acoustic signal has been identified, three acoustic sensors are placed in a row as seen in Figure 8. They should be strategically placed to which the center sensor is showing the shortest distance to the corresponding electrical signal. The sensors are first placed in a horizontal and then in a vertical orientation at the same position, to reduce the triangulation to a two-dimensional solution. Utilizing the PD detector software, the two measurements result in a three-dimensional position, as shown in Figure 10. Figure 11 then illustrates that with both the internal schematics of the transformer and the three-dimensional position, the PD source location can be determined within the transformer.

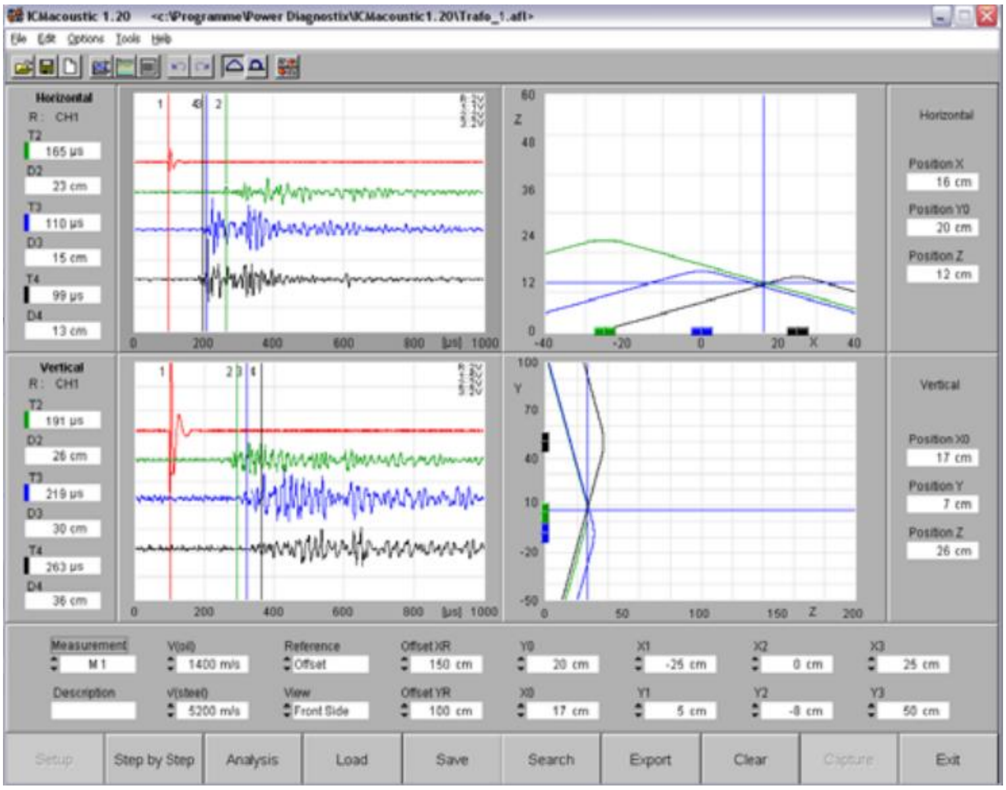

Figure 10: PD detector software analysis of the vertical and horizontal measurements.

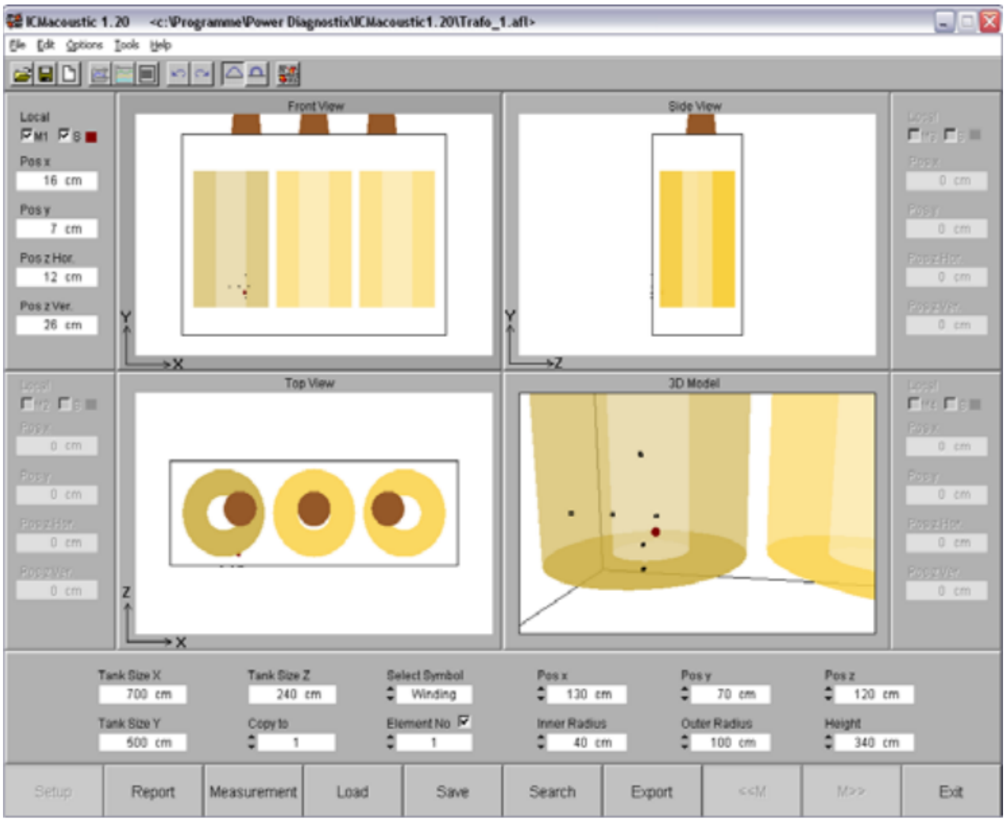

Figure 11: PD detector software rendered position of PD sources determined by vertical and horizontal measurements.

Conclusion

Partial discharge testing is one of the advanced diagnostic tools that can lead to an early detection of defects in a transformer's insulation system. If left unattended, PD activity can result in a breakdown in the insulation and lead to severe damages. Partial discharge testing is already a well-accepted practice for shop floor testing and FAT. The test rooms are usually optimized for PD testing and are vastly different from the conditions faced when performing on-site testing. On-site conditions often require a lot more attention to achieve an acceptable noise level and a good sensitivity while respecting the standards. For diagnostic testing when PD is already known to be present, it can be acceptable to use non-conventional techniques to further acquire and identify PD signals. A PD measurement can produce a PRPD pattern that can be analyzed to give insight into the type of defect and a rough location of the PD activity. Once known, acoustic measurements can be utilized to locate the PD source by using several acoustic sensors. Placing these sensors close to the PD source, ideally with a clear oil path, will allow for a correlation of the electrical pulse and the corresponding acoustic signals. Placing the sensors in a horizontal and then vertical orientation reduces the solution from three-dimensional to two-dimensional. Once the measurements have been performed the PD detector software will provide the three-dimensional location of the PD source, and together with the internal transformer schematics, will provide the location with respect to the internal construction. These testing and analysis techniques can lead to the detection, location, and repair of transformers through on-site testing. This would ultimately lead to an extended life of the asset and avoided outages, which in turn can save a significant amount of resources for transformer asset owners.

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