Application of Immersive Technologies in the Visualization of Partial Discharges in Power Transformers: A Significant Advance in Supporting Maintenance Practices

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ABSTRACT

In recent years, virtual reality (VR) and augmented reality (AR) technologies have been increasingly used by electric utilities. This innovation strategy is in line with the principles of Industry 4.0, where technologies aim to extract the maximum amount of information that reflects the reliability of assets. The possibilities of using VR and AR are significant, such as supporting the management, control, and execution of procedures in power systems, as well as for training and remote assistance. This progress is largely due to the integration possibilities with mobile devices and the modeling capabilities of the process and equipment structures. However, the application of these techniques in the context of maintenance of critical assets in high-voltage direct current (HVDC) systems has not reached the expected scale. In this context, this paper proposes solutions for the development of VR and AR interfaces applied to maintenance techniques for one of the key assets of HVDC: the converter power transformers. More specifically, this paper introduces a methodology based on VR and AR to support acoustic emission (AE) testing for the detection and visualization of partial discharge (PD) sources in power transformers. PDs are a common type of fault in power transformers and their localization is a challenging task. The results of integrating VR and AR provide additional features to the AE technique, such as detailed three-dimensional visualization of the transformer and real-time access to parameters, which allow for a faster and more accurate preparation, execution, and diagnosis of AE techniques on converter power transformers, ultimately reducing maintenance costs.

Keywords: Power transformers, Maintenance, Partial discharges, Acoustic emission, Virtual and augmented reality.

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1. INTRODUCTION

Power transformers play an essential role in power grids by ensuring the continuous supply of electricity. Timely and efficient maintenance of these components is critical to ensuring the uninterrupted flow of electricity. While traditional maintenance methods are effective, some require complex diagnostics that can be improved to increase their accuracy. One example of this is the use of the acoustic emission (AE) testing to detect partial discharges (PDs). PDs are a common phenomenon in power transformers, especially older or poorly maintained ones, and, if left untreated, result in loss of the transformer's dielectric properties. In other words, the insulating material cannot withstand the voltage stresses, resulting in small internal electric arcs (Zhu D et al., 1988).

While there are discussions about more effective methods for detecting PDs in transformers, accurate detection and localization is still a challenge. Despite the advances in software designed to detect and localize of acoustic signals associated with PDs, there are still limitations, such as the lack of graphical detail of the structure under analysis, which makes it difficult to identify the internal components affected by PDs within the transformer.

In this context, virtual reality (VR) and augmented reality (AR) technologies can provide additional capabilities to mitigate these challenges in maintenance and diagnostics. According to Azuma (2018), these technologies are particularly useful for design review, training (Alaraj et al., 2011), equipment operation monitoring, inspection, and maintenance (C. Yan et al., 2014). These examples illustrate the potential of VR and AR technologies to improve maintenance and diagnostics in the power grid industry, and support the claim that they can mitigate challenges and improve time to diagnosis.

Therefore, this paper proposes a solution for immersive experiences in virtual environments with the goal of increasing the accuracy of PD localion in power transformers through the application of the EA test. The use of VR capabilities allow maintenance personnel to immerse themselves in realistic virtual environments that comprehensively and thoroughly represent complex transformer components, providing a distinct advantage over the graphical capabilities of traditionally used softwares.

2. BACKGROUND INFORMATION

2.1. What Are PDs?

PDs are small electrical sparks resulting from the electrical breakdown of gas in a void or in a highly non-uniform electric field (Mohammadi et al., 2009). PDs result in a localized and almost instantaneous release of energy, producing various effects such as chemical products, structural changes in the material, electromagnetic effects, heat, noise, etc. The measurement of PDs is an important task in the maintenance of electrical equipment (Nicoară; Marinescu; Pătru, 2016). For example, these measurements are routine during the lifetime of power transformers (Nicoară; Marinescu; Pătru, 2016). According to (ABNT IEC, 2017) and (IEEE, 2019), PDs are defined as those that partially break the insulation between conductors.

2.2. Types of PDs

PDs can be classified as internal, surface, corona, and treeing. Figure 1 illustrates internal discharges, which occurr in voids or cavities within solid or liquid insulation materials. Surface discharges occur at the interface of different insulating materials. Corona discharges occur due to non-uniform electric fields at sharp points of high voltage electrodes, whether in the air, liquids, or other gaseous insulators. Finally, treeing discharges occur due to the continuous impact of discharges on solid insulating material, forming a conductive channel.

(a) Internal DPs (b) Surface PDs

(c) Corona DPs (d) Treeing PDs

Figure 1 - Types of PDs (Rathod; Kumbhar; Bhalja, 2023)

2.3. PDs in Transformers

PDs are an increasingly common phenomenon in power transformers, especially those that have exceeded their service life or have been poorly maintained. These events result from changes in the structure of the insulating material used in the equipment, leading to the formation of air bubbles and the loss of dielectric properties. The insulating material cannot withstand the imposed stress of voltage without the occurrence of small internal electrical arcs. The occurrence of PDs can lead to the loss of dielectric stability in an insulation system and, if not monitored and addressed, can result in the functional failure of the transformer. This is due to the tendency of a reduction in the dielectric capacity of the insulator to decrease, culminating in a sudden electrical failure (short circuits) (Zhu et al., 2015).

Figure 2 illustrates the three main regions where faults occur in transformers: winding (37.69%), tap changer (31.16%), and bushings (17.16%). These three regions account for 86.01% of occurrences, with the remaining 13.99% in connections (8.96%), core and tank (3.54%), cooling system (1.12%), and current transformer (0.37%).

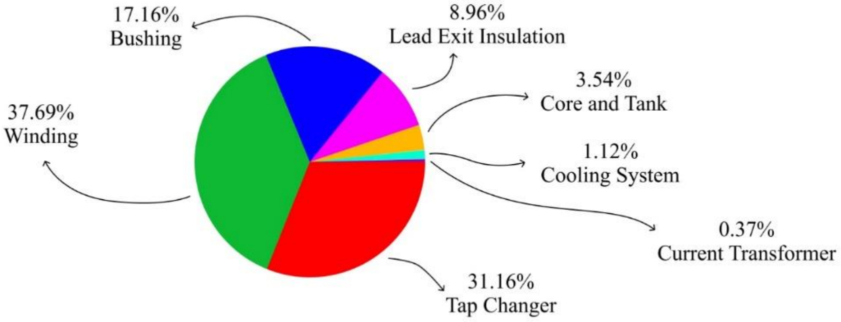


Figure 2 - Probability of defect location in transformers (Tenbohlen et al., 2015) apud (Hussain; Refaat; Abu-Rub, 2021).

2.4. Techniques for PDs Detection

There is ongoing debate regarding the most effective approaches for detecting PDs in power transformers. Accurate identification of the intensity and location of PDs is crucial for maintenance procedures. However, as noted by (Zhenquan et al., 2009), detecting and locating PDs remains a significant challenge.

PDs cannot be measured directly (IEEE, 2019). Physical effects produced by PDs are measured, such as electrical, chemical, acoustic emission, electromagnetic, vibrations, sound, optical, and heat (IEEE, 2019). Each of these methods has advantages and disadvantages in the PD detection process. Table 1 presents the main PD detection techniques in transformers.

Table 1 – Comparison between PD Detection Techniques in Transformers (Hussain; Refaat; Abu-Rub, 2021).

Techniques	**Advantages**	**Drawbacks**
Electrical Detection	Convincing recording of PD signals in laboratory. High sensibility. Low noise level in PD signal. Less signal attenuation	Tricky to implement online. Fake alarm due to greater sensivity. Unreliable for long-term condition monitoring. Affected by electromagnetic interference. Susceptible to noise.
Chemical Detection	Convincing recording of PD signals in laboratory. High sensitivity.	No relation of level of dissolved gas with the distinction of type of fault. No relation between the amount of glucose and intensity of dieletric breakdown.
Optical Detection	Broad variety of chemical and physical parameters can be used. High sensitivity. Immunity for electromagnetic interference. Small size and light weight.	No detection feasible for solid and liquid insulation. Cannot be calibrated.
UHF Detection	Suitable for online PD detection. Improved immunity against external noise. High sensitivity and anti-interference. Reliable and safe against any induced current.	Calibration problem. Expensive. Cannot provide charge quantity of PD.
Acoustic Emission (AE) Detection	Convincing result in real-time. Noise immunity of device for online PD detection. Localization feasible.	Susceptible to environmental noise. Low sensitivity.

Electrical and chemical techniques have high sensitivity but are susceptible to electromagnetic interference (Hussain; Refaat; Abu-Rub, 2021). Optical methods are immune to electromagnetic interference, but face challenges in testability and calibration (Hussain; Refaat; Abu-Rub, 2021). UHF technique offers high sensitivity and immunity to electromagnetic interference (Hussain; Refaat; Abu-Rub, 2021). On the other hand, acoustic emission (AE) techniques, which is particularly relevant to this study, have been developed over the last forty years, showing to be promising solutions.

2.5. AE Technique

AE is a non-destructive technique that detects, locates and monitors microstructural changes in materials by detecting internally generated acoustic waves (Mohammadi et al., 2009). These acoustic waves occur after the release of energy when a material is subjected to stresses that result in deformation, cracks, fissures, and/or dielectric breakdowns These acoustic waves are then picked up by sensitive sensors strategically placed on the surface of the equipment. The AE pulses are amplified and recorded by special softwares. Since there is a very large number of pulses, it is common to record only those within a frequency range that is most characterized by the DPs pattern.

PD location can be determined by using a network of multiple sensors. Conventionally, the Time Difference of Arrival (TDoA) method is applied, where the recorded differences in the arrival times of acoustic signals at different sensor locations serve as inputs for solving nonlinear equations. This mathematical procedure, by elucidating the temporal differences, allows the precise estimation of the spatial coordinates of the PD (Rathod; Kumbhar; Bhalja, 2023).

Each sensor has a signal with amplitude and phase shift (arrival time). A set of equations derived from the difference in the arrival time of the acoustic signal at each sensor is processed by the acquisition software, although this aspect will not be explored in this article. The mathematical aspects behind PD location are as follows:

- Each sensor fixed in the structure has its x, y, and z coordinates.
- At least four sensors are needed for localization (Newton's law).
- A filtering mechanism has to be implemented.
- Each sensor has an amplitude and phase-shifted signal (receive time).

Figure 3 below shows a basic diagram of a PD detection system using the AE technique. These components form functional modules with dedicated functions in the AE system. The data acquisition module, which works together with the AE sensors, has the function of capturing the acoustic signals generated during the test. The data processing module, which has the role of analyzing and filtering the collected data to remove noise. This module also identifies distinct patterns and characteristics associated with potential defects.

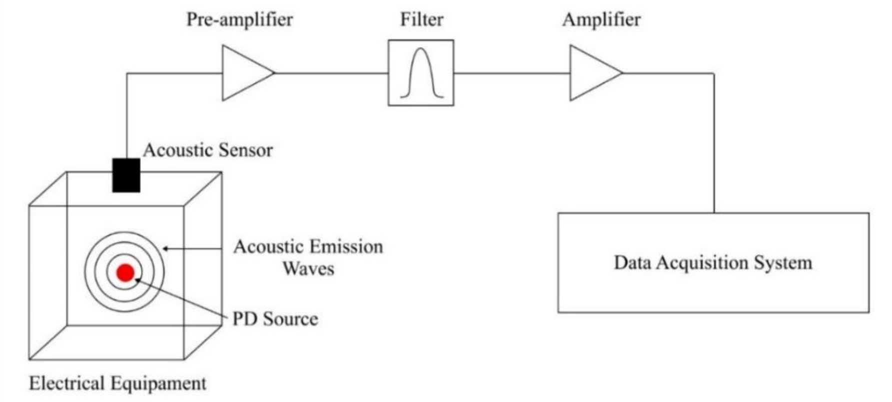


Figure 3 - PD detection system with the AE technique.

There are few manufacturers of commercial AE systems available in the market, with the main players being Physical Acoustics Corporation (PAC) and Vallen Systeme. Other notable contributors to the market, such as Soundwel in China and Dittel in Germany, are also performing admirably. Regardless of the technology employed by these AE acquisition systems, they all essentially follow the processing shown in Figure 3. In this article, the AEwin™ software from Physical Acoustics Corporation (PAC) was used, provided by the Brazilian power company *Eletrobras Eletronorte*, which sponsored the research project. This AEwin™ solution is a dedicated software for the real-time processing of AE characteristics and waveforms.

2.6. Virtual Reality (VR)

VR involves artificially created environments that are perceived by our sensory systems. Like the real environment, i.e., the physical world around us, synthetic environments can evoke emotions, educate, entertain, and respond to our actions. A few years ago, access to such immersive experiences was challenging due to the high cost of equipment. However, with economies of scale and technological advances, these technologies are increasingly being used and explored. There is often a juxtaposition between the real and the virtual, as if the virtual is something that does not really exist. Therefore, for a better understanding, the two concepts introduced by philosophers such as Pierre Levy (2003) are presented below: "Virtual refers to environments or elements synthesized by digital devices that can be reproduced in an immaterial way.", and "Real refers to environments or elements that the user considers to be part of his or her reality."

There are other definitions of VR, some more focused on technology, such as that of Tori and Kirner (2006), who defined it as: “VR is, above all, an advanced user interface to access applications running on the computer, featuring the visualization and movement of elements in three-dimensional environments in real time and the interaction with elements of that environment. In addition, to visualization, the user's VR experience can be enriched by stimulating other senses such as touch and hearing”. There is also the significant contribution of (Jerald, 2015), who summarizes the definition of VR as: “VR is defined as a digitally generated environment that can be interactively experienced as if it were real." According to (Cummings et al., 2012), the variables that define the immersion dimension are:

- Image Quality: Realism and fidelity of image synthesis, including resolution, frequency, texture mapping quality, and level of detail.
- Field of View: The user's field of view when interacting with the virtual environment.
- Tracking: Degrees of freedom, accuracy, response time, and other quality attributes of the tracking system.
- Range: The variety of sensory modalities provided to the user, such as visual, auditory, and tactile.
- Vividness: The quality of the simulation.
- Interactivity: The user's ability to interact with the environment, the environment's response to the user's actions, and the ability to interfere with future events.
- Plot: The fluency, consistency, and quality of the narrative and the behavior of the environment and its elements.

2.7. Parametric Modeling in CAD Systems

Manual parametric modeling based on 2D CAD design is an approach that combines the functionality of CAD software with parametric capabilities to create and modify 3D models in a controlled and flexible manner. This technique allows designers to adjust the dimensions, geometry, and other characteristics of the model according to defined parameters, providing a more efficient integration between 2D and 3D design. Autodesk Inventor software was used to demonstrate the practical results of this research.

3. AE METHOD CURRENTLY APPLIED

The AEwin™ software is a system currently used in the power utility industry. This AE system is dedicated to the acquisition, processing, statistical treatment, and location of partial discharges. These functions aim to simplify analysis and visualization tasks, such as fast data storage, graphics, which is essential for managing data of interest. Using several sensors positioned on the surface of the transformer structure to be monitored, the system detects partial discharges and identifies their coordinates, and presents a parameterized visualization according to the desired analysis.

The AEwin™ software provides a 3D visualization of the detected clusters and events. This 3D visualization is used for PD visualization. However, for real transformer references, components such as AT and BT bushings are manually inserted into the geometry for visual understanding. This procedure is considered manual customization because the software's geometry lacks graphical elements of the transformer, making it a generic 3D geometry. Figure 4 illustrates the graphical customization applied by the essayists apply to the graphical representation of AEwin™ by editing the reference graphical elements (Ln and Nn) in the selected software's 3D geometry, which is closest to the transformer.

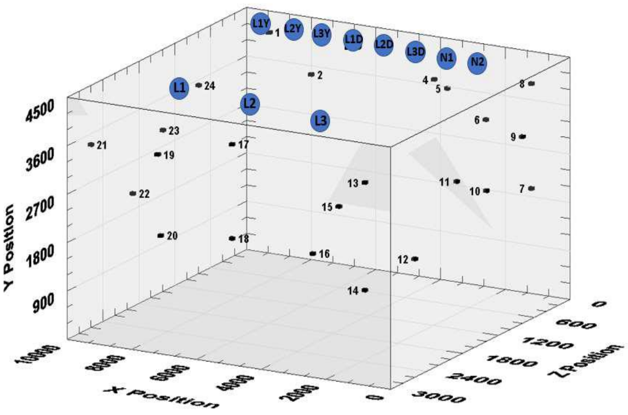


Figure 4 - Customization in the 3D graphical representation of AEwin™ for AE testing in a power transformer.

Currently, at the Brazilian power company *Eletrobras Eletronorte*, the AE test does not have standards by model and type of transformer. Therefore, it is the responsibility of the test team to work on a case-by-case basis in the preparation phases. As a basic requirement for the test, consultations such as the electrical and dimensional design of the transformer are necessary prerequisites for good planning. Another aspect that requires a lot of effort from the team is the strategic positioning phase of the acoustic sensors. Each transformer design has particularities that must be considered when fixing the sensors.

4. OPPORTUNITY FOR IMPROVEMENT

AEwin™ is a system dedicated to the acquisition, processing, statistical treatment, and localization of partial discharges (MISTRAS, 2024). Using several sensors positioned on the surface of the structure to be studied, the system detects partial discharges, identifies their coordinates, and presents a visual result through a 3D map. However, the software visualization does not provide a clear identification of the specific areas of the structure where these events are occurring. In order to analyze this data in more depth and to effectively integrate the technology into maintenance processes, it is imperative to improve the visualization of this process.

5. PROPOSED SOLUTION

Essentially, a proof of concept is proposed to provide additional graphical resources in the AE technique. The solution focuses on enhancing the visual capabilities of the AEwin™ software used by the Brazilian electric power company *Eletrobras Eletronorte* for transformer health monitoring. This enhancement allows maintenance professionals to visualize AE results in virtual environments, providing intricate details of the internal components of the transformer being analyzed. The innovative proposal incorporates immersive VR technologies, aiming to improve the accuracy of diagnosing the location of acoustic signals with partial discharge characteristics.

The application of immersive VR technology in predictive maintenance for power transformers in electric energy companies is expected to be a promising revolution in traditional practices. These technologies not only optimize operations, but also significantly improve diagnostic effectiveness.

6. DEVELOPMENT OF THE PROPOSED SOLUTION

To develop the methodology, a three-phase transformer manufactured in 2010 was selected by the utility company. This transformer operates in the HVDC system and has a unique design, with dimensions of 10.50 meters in length, 3.30 meters in width, and 4.0 meters in height.

The first step of the solution under development is to create a virtual replica of the model using Autodesk Inventor and the manual parametric modeling process. Since the application require design details of the transformer, particularly internal components, it was necessary to create an internal and external replica of the model. This part will serve as a reference for the points generated by AEwin™. Some steps of this modeling work are shown in Figure 5. From left to right, we have the dimensional reference of the transformer in a 2D CAD design, followed by the evolution of the model of the active part, and finally, the integration of the active part with the external structure of the transformer.

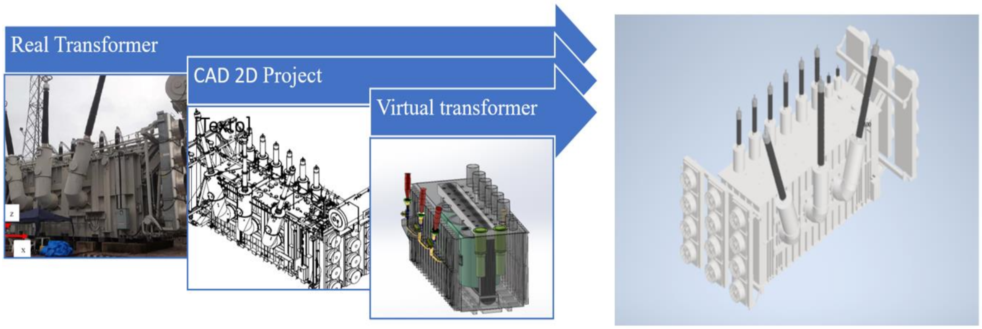
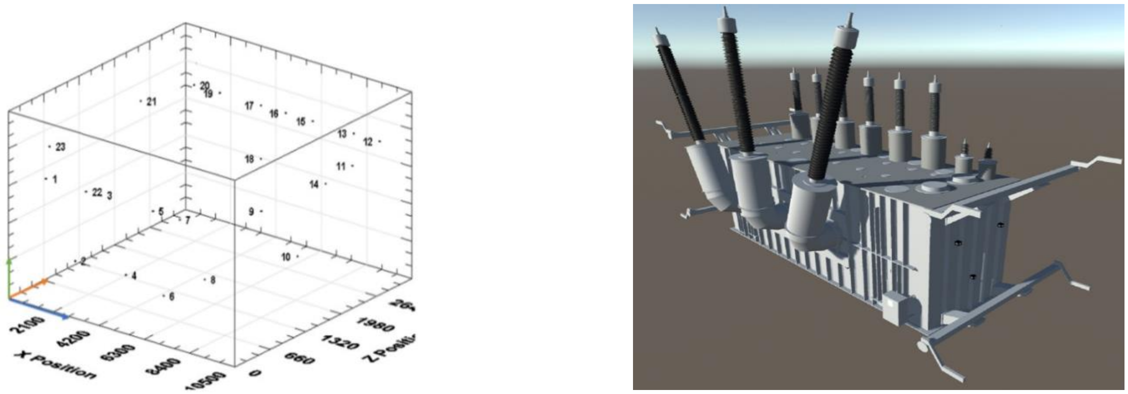


Figure 5 - Steps of the modeling process.

The next step was to create an environment would support both the model and the coordinate data generated by the AEwin™ software, representing the acoustic activities of interest in the analysis. In other words, the proposed system involves the creation of a realistic virtual environment of the transformer, integrating the necessary information from the AE test to compose the 3D graphical representation. It was decided to implement the solution within Unity 3D™, importing CSV (Comma-Separated Values) files from the AEwin™ software to the immersive platform using scripts. Data such as sensor coordinates, and cluster centroids were adjusted to align with a single reference point (x, y, z) of the virtual transformer.

Figure 6 shows a comparison of the graphical feature available in the AEwin™ software (Figure 6(a)) with the proposed approach (Figure 6(b)) that incorporates VR resources.



(a) Graphical interface in AEwin™.

(b) Graphical interface in Unity 3D™.

Figure 6 – Comparison between the graphical representations in AEwin™ and Unity 3D™.

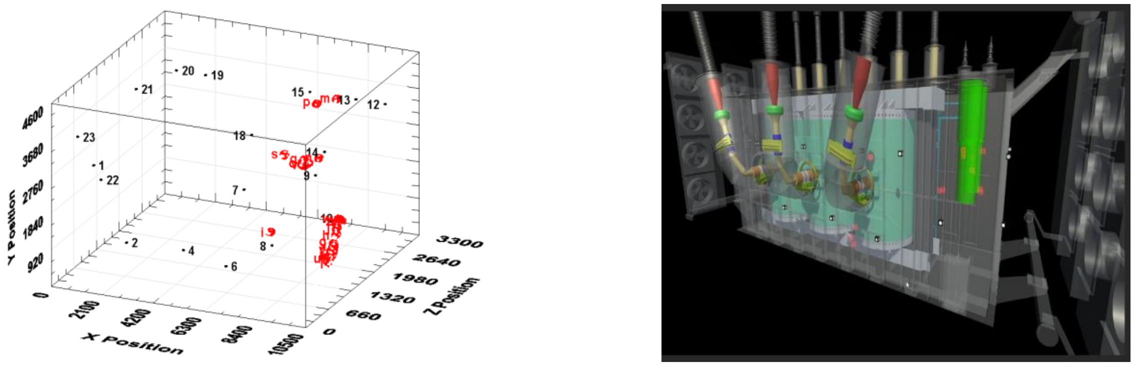
As shown in Figure 6, the focus is on the magnetically attaching of sensors to the external structure of the geometries. These AE sensors are strategically placed and numbered from 1 to 23. It's worth noting that a more realistic understanding of what is being monitored is achieved through a faithful representation of the transformer using the VR interface. In addition, Figure 6(b) shows that the radiators have been removed from the transformer model to provide a clear view of the sensor locations on the right side.

Throughout the development and application period of the methods presented in this article, potential users from *Eletrobras Eletronorte* were involved. Various methods were used to analyze the system requirements, such as meetings, presentations of transformer projects, and responses to modelers' requests. The main results are illustrated in the following section.

7. RESULTS AND DISCUSSION

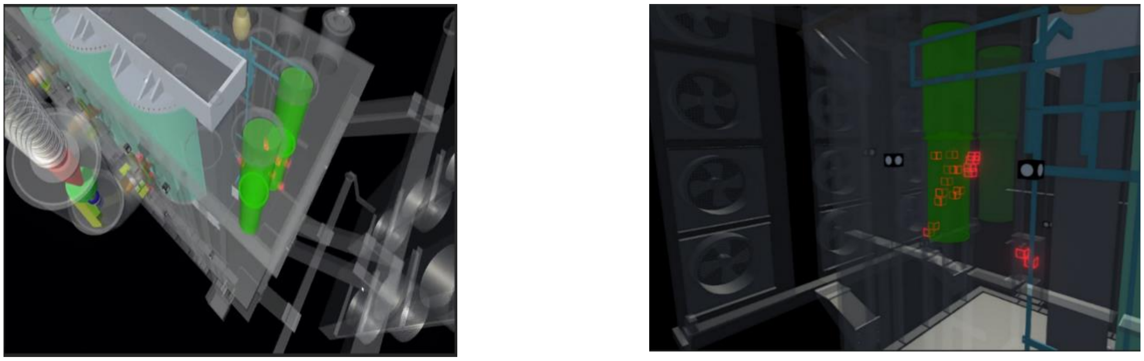
As a case study, AE technique monitors data from the same transformer where the parametric modeling process was presented. The AE monitoring of this transformer lasted continuously for 24 hours and was performed by the company's own experts in January 2022, under varying load conditions to induce greater electrical and thermal stress. In addition, experts monitored key parameters for comprehensive analysis, such as temperature, electrical current, and tap changer operating moments. The signals were collected and processed using the AEwin™ software, with filtering settings to obtain the best representation of signals with PD features.

The results were carried out through a graphical comparison between the current cluster visualization model (red cubes) and the proposed model using VR technology. The clusters represent groupings of detected acoustic signals with higher energy. The centroids of these clusters are georeferenced both in the 3D graphical representation of the AEwin™ software and in Unity 3D™, as shown in Figure 7. The criterion for the analysis the results was to evaluate the advantages of each visualization method in terms of precision and comprehensibility for the development of a transformer health diagnosis. Figure 7 shows the plots of the visual locations of the clusters generated after 24 hours of acquisition.



(a) – Cluster visualization in 3D graphical in AEwin™.

(b) – Cluster visualization in 3D graphical in VR.



(c) – Top-down view of clusters in 3D graphical representation in VR.

(d) – Side angle view in 3D graphical representation in VR.

Figure 7 - Comparison of visualization between the current EA methodology and the proposed one with VR integration.

The 3D visualizations from the AEwin™ software and the proposed methodology using the immersive environment are presented. In Figures 7(b), (c), and (d), it can be seen that the 3D visualization of the clusters in VR allows the identification of areas of interest with greater accuracy, including the proximity of internal components to the transformer. On the other hand, the 3D visualization shown in Figure 7(a) only allows the identification of a positional reference in the geometry, without, however, understanding which internal components of the transformer require more attention. Another advantage of the VR feature is the ability to explore the structure of the transformer where the clusters are located. It is possible to disassemble, exclude, or make transparent certain components for a better visualization of the PDs.

Another observation, supported by both the current and the proposed methodology, is that the acoustic activity recorded during the entire test is mainly concentrated in the region near the taps switches. According to the probability of defects presented in Figure 2 (Section 1.3), taps switches are responsible for 31.6% of the internal defects in the transformer. This visual indication can be confirmed when the transformer and manufacturer specialists compared the moments of acoustic detection with the operation of the taps switches during the 24-hour monitoring. In this case, after a joint analysis with the manufacturer, it was concluded that the concentrated acoustic activity in this region of the switch toggles is not a cause for concern, but rather requires continuous monitoring.

8. CONCLUSIONS

Based on the results, the integration of immersive technologies into established maintenance tools, such as the AE technique, demonstrates a significant improvement in the visualization of PD sources. The inclusion of this visual resource allowed for a more deeper understanding, particularly using advanced graphics driven by VR. This approach allows for a more detailed analysis of areas where sensors have detected increased acoustic activity within the transformer. As a result, technicians can accurately identify regions with distinctive PD characteristics, optimizing the analysis and interpretation of results. The virtual visualization of the transformer's interior contributes to a better understanding of internal conditions, making it easier to identify potentially aging or worn components.

Moreover, the benefits associated with immersive technologies include the standardization of the test, considering the allocation of acoustic sensors, a crucial aspect in the preparation that is influenced by the individual design of each project. At this stage, it is possible to virtually see sensors location and adjust them, providing a more personalized and adaptable approach to different transformer models. In conclusion, the results highlight the advances that this proposed enhancement adds to PD source visualization, leading to more accurate diagnostics.

9. ACKNOWLEDGEMENTS

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