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Detection, Classification and Location of Sources of Partial Discharges Using the Radiometric Method: Trends, Challenges and Open Issues

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ABSTRACT In this article, it is provided a comprehensive survey on the most relevant research in the area of detection, classification and location of partial discharge (PD) sources using the radiometric or ultra high frequency (UHF) method, focusing mainly on the works related to the use of antennas. To the best of the authors knowledge, this is the first review paper that focuses on the application of antennas based on UHF method in the complete diagnosis of PD. Specifically, it is first presented the main contributions to the development and optimization of UHF sensors for application in the detection of PD sources. Second, articles that used the UHF method to identify different types of PD in high voltage equipment are described. Finally, the main contributions regarding the location of sources of defects using the radiometric method are presented. Summary of works in the area of UHF detection sensors, PD classification and PD location, with their respective contributions, are shown. Finally, research trends, challenging and open issues are discussed. The purpose of this article is to provide important information about the complete diagnosis of PD, which could be used to guide the development of more efficient techniques in this research area.

INDEX TERMS Antennas, classification, detection, location, partial discharge, radiometric method, UHF method.

I. INTRODUCTION

For the reliable operation of the high voltage equipment that composes the electric power system, the insulating system of these equipment needs to be in conditions to guarantee its proper operation. In the occurrence of failures in the insulation systems, defects such as short circuits, equipment failure, damage to structures and others can occur, resulting in significant expenses for electricity utilities such as maintenance, repair, replacement of equipment and regulatory fines due to the interruption of the power supply as a result of an equipment failure. Before the failure, the insulation systems of high voltage equipment, such as insulators, power transformers, instrument transformers, surge arresters and others, present the intense activity of a phenomenon called partial discharges (PD) [1].

PD can be defined as low-intensity electrical discharges that partially short-circuits regions of the insulating material subjected to intense electric fields [2]. The continuous PD activity on the insulating material results in its gradual degradation, which can lead to a complete dielectric breakdown and, consequently, to the failure of the high voltage equipment. Therefore, the continuous monitoring of PD activity in the aforementioned equipment can be used as a failure prevention tool, indicating in advance the development of future dielectric problems.

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The conventional methodology used for PD detection is described in IEC 60270 [3]. This method consists in the measuring of current pulses emitted during the PD occurrence. For this purpose, coupling capacitors are connected in parallel with the monitored equipment. However, the use of coupling capacitors represents a limitation for the method, since an electrical connection between the capacitor and the equipment becomes necessary. In addition, the coupling capacitor can assume large physical dimensions for applications at high voltage, characterizing the method as highly invasive, turning it impractical for equipment continuous monitoring.

In order to overcome the limits imposed by the method standardized by IEC 60270, researchers studied several alternative methodologies for the continuous monitoring of internal PD activity in high voltage equipment [3]–[8] as presented in Fig. 1. One of the most efficient methods consists in the detection of electromagnetic waves emitted by the PD current pulses using antennas in the ultra high frequency (UHF) band (300 MHz-3 GHz).

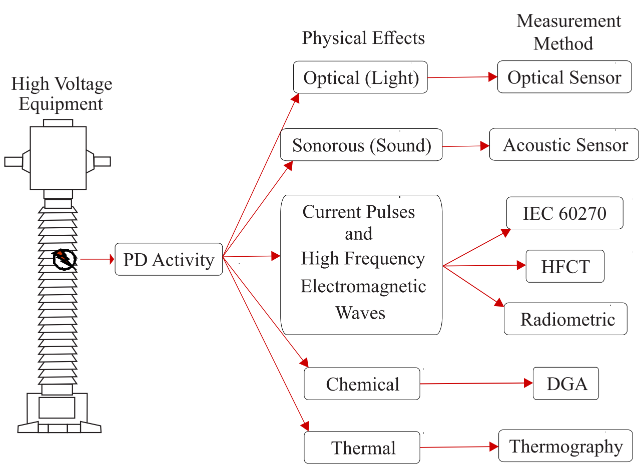

FIGURE 1. Phenomena associated with the PD activity and their respective methods of measurement.

One of the main advantages offered by the UHF or radiometric method for PD monitoring is the elimination of the electrical connection between the receiving antenna and the monitored equipment. In addition, the high frequency operating range isolates the system from detecting common interference in substations, such as switching in power electronics equipment and corona discharges, since the signals generated by these discharges have components with significant energy up to frequencies between 200 and 300 MHz [6]. Therefore, the radiometric method is characterized as a promising non-invasive technique for the continuous monitoring of high voltage equipment. In 2008, the working group A2.27 of Cigré recommended that power transformers must be manufactured with the provision of at least four spaces (dielectric windows) for the allocation of UHF sensors [9].

The application of the UHF method is efficient not only in the detection of the electromagnetic waves emitted by the PD pulses, but also in the classification (internal, surface and other discharges) and location of defects related to the occurrence of these discharges [10]. From the combination of the information collected from the detection, classification and location of PD, it is possible to carry out a complete diagnosis of the operating status of the evaluated equipment and, in general, of the substation. In this way, the PD monitoring using the UHF method represents a support tool of great utility in predictive maintenance processes, aiding in the classification of the severity of the defect, its location and the urgency of performing or not the replacement or repair of the equipment. The diagnosis process from the UHF method is summarized in Fig. 2

In the literature, several works concerning this research topic have been addressed. The use of UHF sensors in the detection and location of PD had its first application in studies performed by Hampton and Meats [11], in which PD were detected and located using capacitive sensors in a 420 kV gas insulated substations (GIS) belonging to the South of Scotland Electricity Board group. The detection results showed greater sensitivity in the frequency range of 600-900 MHz and an error of only 1 meter at the source of the defect analyzed within a 40 meters length structure.

The successful results obtained in [11] encouraged several studies in the area of GIS monitoring through UHF sensors. In subsequent years, the investigations were focused on the consolidation of the UHF method in real operating GIS, such as in the works developed in [12]–[16]. Therefore, already in the 90s, the UHF method proved to be promising for the measurement and location of PD sources, since the structural simplicity of the GIS allows the location of the PD in a single dimension (in this case, only the distance to the sensors).

In 1996, the use of computer simulations to assist the location of PD in GIS was introduced [17]. For this purpose, the UHF PD signals were simulated from a combination of transfer functions of the system, in order to associate the sensor's output voltage to the PD source. For the validation of the proposed model in [17], the authors made comparisons with the analytical results from tests carried out in a linear coaxial cavity of 3.6 m length and with a diameter comparable to a real GIS. The distances between the signal source (Gaussian pulse) and the UHF sensor were 0.9, 1.2 and 1.5 m, respectively. From the proposed method, an accuracy above 88% in the location of the defects was achieved.

After the consolidation of the UHF method for the detection and location of PD in GIS, researchers expanded the application of the method to other high voltage equipment, mainly high voltage cable connections [18], open area substation equipment [19], and power transformers [20].

For power transformers, laboratory tests were performed in [20] with the objective of simulating PD sources inserted in a tank filled with transformer oil. For the detection of the signals, a spiral antenna was used and, for the validation of the UHF method, acoustic sensors were applied simultaneously. The results obtained in laboratory demonstrated good sensitivity of the UHF method, being equivalent to the acoustic method. However, more differentiated discharge

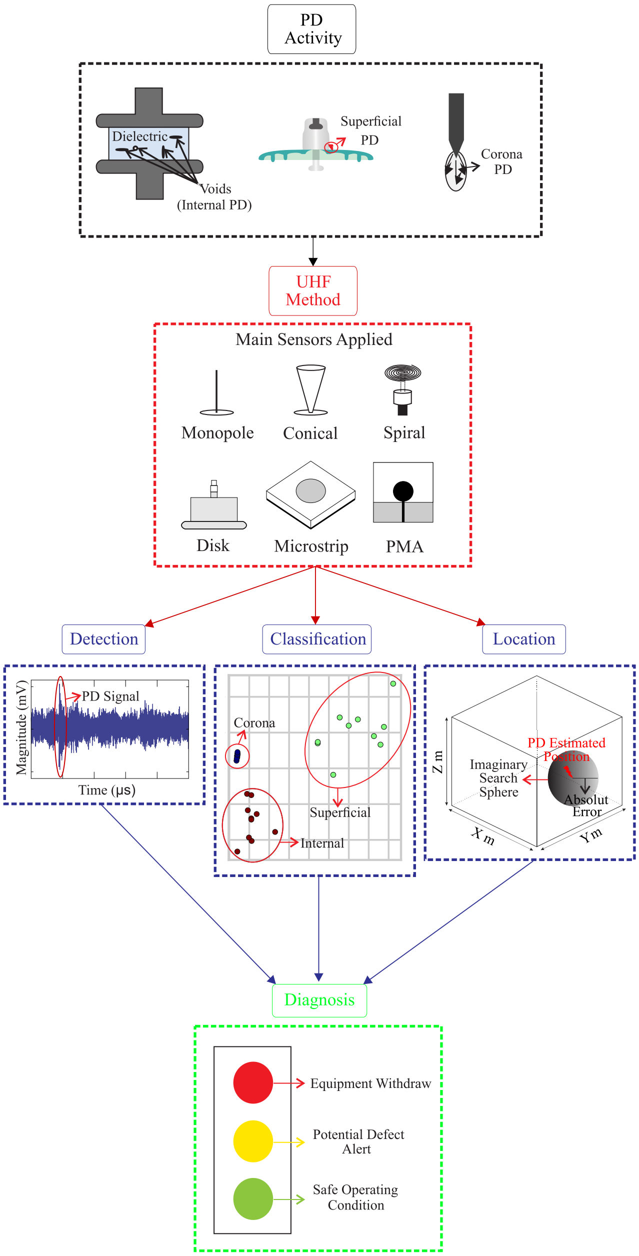

FIGURE 2. Summary of the operational condition diagnosis process of high voltage equipment using the UHF method.

patterns were observed in the responses obtained by the UHF method, which facilitates future applications concerning discharge classification. In addition, signal attenuation tests for different distances from the discharge source were performed. The results in [20] demonstrated a much smaller signal attenuation for the UHF method, when compared to the signals obtained by the acoustic method. After two years, tests described in [21] were carried out to detect PD in an oil cell. The discharges were generated through a tip-plane arrangement immersed in the oil cell and the results obtained by the authors demonstrated that the propagation of the electromagnetic waves emitted by the PD had more significant energy components for the frequency spectrum corresponding to 300-1500 MHz, contributing to the range definition of the UHF sensors designed for the PD detection.

Over the years, investigations continued to be developed with the objective of improving the application of the UHF method, seeking new techniques for coupling sensors in the structure of the monitored equipment. As an example, it can be mentioned [22], in which it was verified in a GIS that the use of dielectric windows increases the sensitivity of the discharges detection by the sensors. In addition, the use of a dielectric window makes the measurement less invasive, allowing the sensor to be withdrawn from operation at any time. The authors justified in [22] that the improvement in the visualized sensitivity and bandwidth is due to the increase in the dielectric constant of the propagation medium, caused by the use of the dielectric window as a superstrate.

Unlike high voltage cables and GIS, where the location of defects can be carried out in only one direction (single axis), the location of PD sources in power transformers and open area substations becomes a three-dimensional (3D) problem in which the source must be defined in spatial coordinates (x, y, z), making it a major complexity task with respect to the mathematical and practical terms [23]. In addition, the presence of obstacles between the sensors and the PD source, such as the transformer windings and the various equipment in a substation, result in reflection and refraction phenomena of the electromagnetic waves emitted by the defect, causing significant errors in the location algorithms, especially when applied in a 3D space.

Considering the location of PD sources in 3D spaces, the use of three UHF sensors and a geometric model of the power transformer was proposed in [23] for the location of PD sources. The numerical model adopted in [23] consisted of the representation of the transformer as a 3D matrix composed of cells of equal sizes in the coordinates x, y, and z. In each cell, a propagation speed is assigned and the arrival time is calculated for each of the three allocated sensors. In this way, the location is made from comparisons between the time estimated by the numerical method and the time measured in practice within a specific tolerance.

Applying the methodology proposed by Yang and Judd [23], in [24], three UHF distributed disk-type sensors were installed, by means of a dielectric window, in a single-phase transformer of 18 MVA and 132/25 kV. The main motivation for the studies in [24] was the existence of an internal defect in the equipment that had been detected during the dissolved gases analysis (DGA), but that was not visually identified by the maintenance team. For the location of the defect, the authors developed a triangulation algorithm that uses the times differences of arrival (TDOA) between the signals, calculated by the cumulative energy method, in each of the sensors distributed in the equipment tank. From the developed algorithm by the authors in [24], it was possible to estimate the location of the defect and, when performing a new visual inspection, the defect was located with only 15 cm of error in relation to the one calculated by the algorithm.

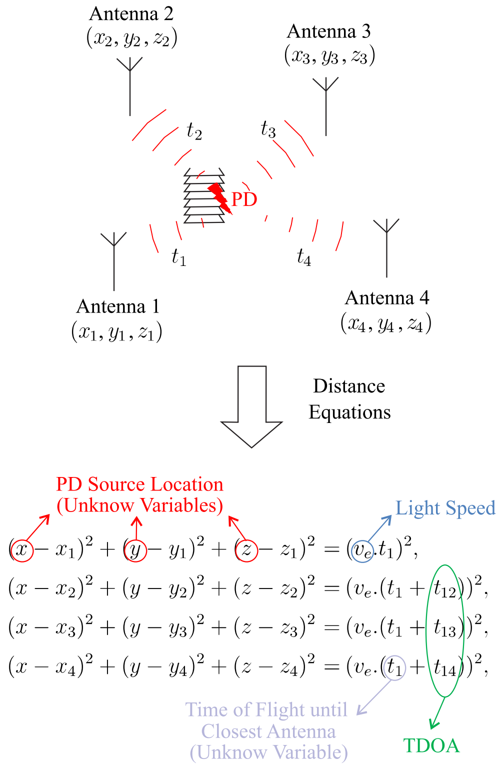

FIGURE 3. Conceptual view of a TDOA-based PD location system.

The conceptual view of a TDOA-based PD location system can be visualized in Fig. 3.

In 2005, the UHF method was also studied in a practical way for the location of defective equipment (PD sources) in open area substations [25]. In the aforementioned work, the authors used four discone antennas with an operating range of 100 MHz-1 GHz and the TDOA algorithm to locate sources of PD in laboratory and at the substation. The antenna array was tested under two types of arrangement. The first consisted of a rectangular configuration in which the antennas were spaced 3 m apart. For the second arrangement, the authors applied a Y configuration in which the antennas were spaced 2 m apart. To assist in the arrival time extraction process, the authors applied the cross correlation method between the signals detected by each antenna. Despite occupying a relatively larger physical space, the rectangular arrangement proved to be more effective than the Y arrangement, resulting in a range up to 15 m in the location of PD sources. The authors stated that the proposed method has high accuracy in locating up to 5 m of distance between the arrangement and the source of the defect. For distances between 5 and 15 m, the location errors can reach up to 2 m. Even so, the results were promising for the detection of PD in open area substations.

The results of the studies presented in this section showed the potential of the UHF technique in the monitoring of high voltage equipment, being more complete and accurate than others already consolidated in the area, such as DGA and acoustic sensors, for example. Since then, research efforts

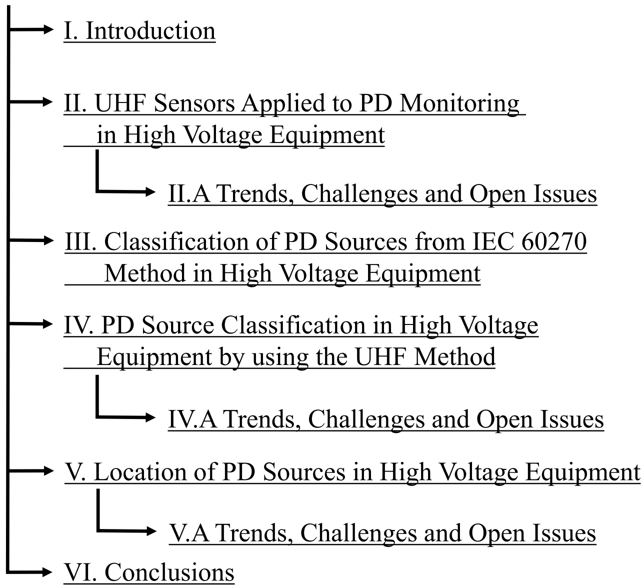

FIGURE 4. The structure of this article.

have been carried out with the objective of improving the radiometric method, seeking new location algorithms; new techniques for extracting attributes for classification; and the improvement in detection, aiming at the development of sensors optimized in cost, sensitivity, dimension and bandwidth that are applicable in the PD detection, in addition to the search for methodologies for calibrating the sensors in terms of apparent charge, a process still limited to the conventional IEC 60270 method [3].

In this article, a bibliographic review on the most relevant research in the area of detection, classification and location of PD sources using the radiometric method is presented. To the best of the authors knowledge, this is the first review paper that focuses on the application of radiometric method in the complete diagnosis of PD, namely detection, classification and location. Unlike other papers in the area [26]–[32], in this work is presented a strong historical background in the search fields of UHF sensor development for PD signal detection, classification and separation of PD sources, and the application of the UHF method in the location of sources of defects from TDOA-based algorithms, covering more than three decades of works during the analysis presented. Based on the historical analysis carried out, research trends, challenging and open issues are identified and discussed in this paper. Therefore, the main purpose of this article is to provide important information about the complete diagnosis of PD that could be used to guide the development of more efficient and new techniques in the research area of PD monitoring by means of UHF method. For a better understanding of this paper, Fig. 4 highlights the structure of this work.

II. UHF SENSORS APPLIED TO PD MONITORING IN HIGH VOLTAGE EQUIPMENT

In 2006, the insertion of a UHF spiral type sensor via an oil valve in a 220 kV and 63 MVA transformer was verified in [33]. The authors justified in their work that the use of dielectric windows may not be feasible in cases of older transformers that do not have adaptive inspection windows in their tank. For the validation of the studies, a disk sensor in a dielectric window was used. The spiral sensor developed in [33] was successful in detecting the pulses of discharges generated in the transformer tank, presenting greater signal intensity mainly for frequencies close to 500 MHz. The results obtained by the authors demonstrated the flexibility in the way of PD detection in transformers, which can also be performed efficiently via the equipment's oil valve. However, the use of sensors via the oil valve does not allow the use of signal triangulation algorithms for the location of defects in the transformer, since there are normally no more than three oil valves in power transformers.

The first use of a rectangular microstrip antenna coupled to a dielectric window is presented in [34] for PD detection in a GIS. The antenna was simulated using the high frequency structure simulator (HFSS) software and built with a coaxial probe feed for a substrate composed of a 9 cm thick air layer. The analysis of its performance parameters, carried out by means of a network analyzer, showed that the voltage standing wave ratio (VSWR) was lower than 2 in a frequency range of 340-440 MHz, presenting peak gain equals to 5.38 dBi. The developed antenna was tested with the aid of IEC 60270 method and installed in a 220 kV GIS. The results obtained by the antenna showed the PD occurrence with an intensity of 232 pC. Despite not covering the entire frequency range of PD activity, the antenna developed in [34] showed results that stimulated the application of this type of antenna in the PD detection.

The insertion of UHF sensors via the oil valve in transformers was evaluated again in [35]. Unlike [33], quarter wavelength monopole antennas were analyzed. Several antenna were investigated, namely, straight wire, conical, zig-zag, helical, spiral, monopole disk, flat-plate and trapezoidal types. Among the evaluated antennas, the conical type antenna obtained the best performance both in the simulation, with good results of gain and coefficient of reflection in the frequency range of 500-700 MHz, as well as in the laboratory tests carried out in a 66/11 kV transformer tank with 10 MVA. After simulations and laboratory tests, the structure was inserted into a 1500 MVA and 330/275 kV transformer. During the monitoring, PD pulses were detected by the conical antenna and verified by the IEC 60270 conventional method with a value of 500 pC. Despite presenting the use of alternative antennas for insertion via the oil valve in transformers, as well as in [33], there is a limitation regarding the application of location techniques due to the number of oil valves available in the equipment.

Three types of microstrip antennas for application on a dielectric window were studied in [36]: bow-tie, spiral and log-spiral. All of them were designed using a printed circuit board (PCB) with a diameter of 17 cm. In addition, the straight wire and conical monopole structures for insertion via the oil valve were checked again, respecting the dimensions specified in [35]. All antennas were simulated using computer simulation technology (CST) microwave software and tested in laboratory using a tip-plane arrangement in conjunction with the IEC 60270 method. The conical and log-spiral type sensors showed better performance in both simulations and laboratory tests, showing good results in detection sensitivity, mainly for frequencies around 345 MHz. Moreover, in [36], it can be verified that, in addition to enabling the use of location algorithms, the use of appropriate antennas for application in dielectric windows also results in better PD detection sensitivity performance compared to sensors installed via oil valve.

In [37], the interaction between the electromagnetic wave emitted by a PD and a microstrip antenna was mathematically analyzed. The authors justified in their work that this type of analysis is necessary, since the characteristics of a microstrip antenna are well known for continuous wave conditions and not for wave pulses, such as PD. In their analysis, the electric and magnetic fields were described by analytical functions, while the antenna was represented by a circuit designed according to the transmission line method. The circuit was subjected to simulated voltage and current pulses. The results showed that the faster the pulses, the better the response in resonance of the representative circuit of the microstrip antenna. Considering that the pulses of PD extend to the order of GHz, it was concluded that the use of the microstrip antenna can be well explored in PD detection. In view of their constructive similarities, the analyzes and conclusions exposed in [37] for microstrip antennas can be expanded to the application of printed monopole antenna (PMA) in PD detection.

A dipole-type microstrip antenna was developed in [38] for application in dielectric windows, with a central frequency of 400 MHz. The material used was a double-sided PCB with a thickness of 1.6 mm and relative permittivity equals to 4.3. The built-in antenna had a bandwidth of only 40 MHz. For better response in the pulses detection, the antenna was connected to a power amplifier developed by the authors. The antenna-amplifier arrangement was compared to the commercial UHF sensor LDA5/U1 in measurements of signals emitted by a device that generates PD pulses. The results were satisfactory, approaching the response obtained by the commercial sensor used, attesting the efficiency of the use of microstrip antennas coupled to dielectric windows.

In [39], a microstrip antenna for insertion via an oil valve was developed. The antenna was simulated using the HFSS software and designed for four resonance frequencies: 680 MHz, 900 MHz, 1100 MHz and 1270 MHz. After the simulations, the antenna was built and subjected to laboratory and field tests. In laboratory, an acrylic chamber of $1.2 \times 0.6 \times 0.8$ m^3 filled with oil was built. A PD source with apparent charge values of 50 pC, previously measured by the IEC 60270 method, was inserted into the chamber. The antenna developed in [39] presented amplitudes around 28.3 mV at its terminals during the PD occurrence in the arrangement. The methodology applied by the authors in [39] allowed an increase in the operating range of UHF sensors built on the basis of microstrip antennas, compensating for the narrow band characteristic of this type of antenna. However, this methodology is only applicable in the case of installation via an oil valve, resulting in practical limitations for the use of location techniques, as previously mentioned.

An antenna with fractal geometry for PD detection by means of dielectric windows was developed in [40]. The main objective in [40] was to develop a compact antenna (lower than 20 cm) that had the maximum resonance modes in the 300 MHz-1.5 GHz range of interest. For this, an antenna was developed using a fourth order Hilbert fractal. To achieve the final structure presented, exhaustive simulations with respect to the length of the antenna and feeding positions were carried out. Considering a VSWR lower than 5, the operating band of the final structure corresponded to the 300 MHz-1 GHz band. Despite the complexity in the project, laboratory tests in an oil cell for two inserted defects (corona and superficial discharges) showed good results in PD detection by fractal antenna, registering values of 30.6 and 47.6 mV for apparent charges of 33.88 and 51.36 pC, respectively. However, the consideration of a VSWR lower than 5 to define the operating range of the antenna implies in reflections up to 44% of the energy of the signals impacted on the antenna patch, resulting in considerable losses of detection sensitivity for different frequencies of their operating range. Thus, it is necessary to analyze other miniaturization methodologies that preserve the bandwidth and sensitivity of detection of the antenna. In Fig. 5 is presented a schematic of the PD measurement setup applied by [40] using the proposed fourth order Hilbert fractal antenna.

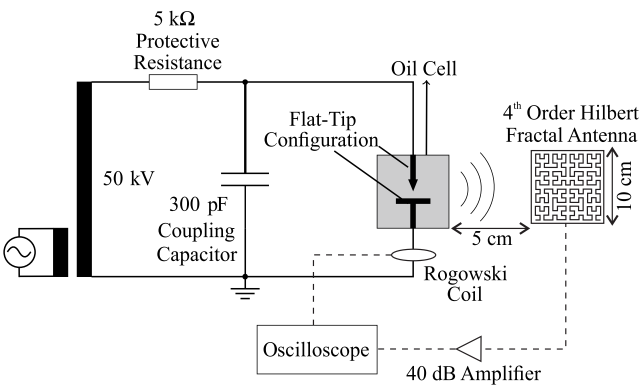

FIGURE 5. **Schematic of the PD measurement setup applied by [40] using a Hilbert fractal antenna.**

One of the first PMA designed for PD detection was presented in [41]. The PMA had an operating range that partially covers the very high frequency (VHF) and UHF spectra, containing the 120 MHz-800 MHz band. Due to its low operating frequency, the projected antenna had a considerable dimension, with a length and width of 70 cm and 64 cm, respectively, limiting its practical application in PD detection. Thus, the PMA developed in [41] was presented only computationally. Despite not having carried out practical tests for PD detection, the work developed in [41] was one of the pioneers to adopt the conception of the PMA use in the PD detection, stimulating the study of this type of structure in UHF monitoring in the subsequent years.

In [42], it was analyzed, by means of simulations, the optimization of the bandwidth of a microstrip antenna through the union of two different spiral antennas: the archimedian spiral antenna (ASA) with two arms and the equiangular spiral antenna (ESA). The built antenna was called planar complex spiral antenna (PCSA) and is composed by the ASA in its central part, responsible for the frequency range of 300-700 MHz, and by the ESA in the rest of its structure, completing the desired bandwidth (700 MHz-1.5 GHz). The projected PCSA had a diameter of 19.1 cm, however, it was necessary to use a substrate with relative permittivity $\epsilon_r = 10.7$ and a thickness of 2.5 mm. Despite having sufficient bandwidth to cover the entire spectrum of the main PD activity, the difficulty in determining the optimal number of turns combined between the two antennas used and the complex construction process necessary to unite the two structures, make the PCSA complex in terms of design and assemble, significantly limiting its practical application in PD detection.

The bandwidth of a PMA has been optimized through changes in the geometry of its rectangular radiating element, as described in [43]. The final structure, simulated using HFSS, reached VSWR < 2 for the 500 MHz-1.5 GHz frequency range. The final dimensions were 25×20 cm^2, with unspecified substrate of thickness equals to 2 mm. The optimized antenna was built and tested in a network analyzer, in which the VSWR values were very close to the simulated ones, with VSWR lower than 2 for the frequencies of 565 MHz-1.5 GHz. In addition to the VSWR tests, measurements were also made for the radiation and gain pattern of the built-in antenna. The results showed an omnidirectional radiation pattern with an average gain of 2.32 dBi in the 500 MHz-1.5 GHz frequency range. Finally, PD measurements were made on 110 kVA switching panels using the developed PMA and a straight wire monopole antenna as reference. During the measurements, it was verified that the PMA developed by the authors had a sensitivity 3.5 times higher than the reference antenna, attesting the applicability of PMA antennas in PD detection.

The authors in 2017 [44] adapted their PMA previously presented in 2014 [41] to achieve more suitable dimensions for application in PD detection. In addition, the operating range of the PMA antenna has also been changed, now with range of 350 MHz-1.38 GHz. The PMA dimension was significantly reduced in comparison to the structure designed in its previous work [41], with length and width values equivalent to 24 and 20 cm, respectively. Unlike his previous work, the final model designed was built and subjected to tests of reflection coefficient, radiation and gain pattern. For all the mentioned tests, the simulated and practical results presented good agreement, with emphasis on the gain, which presented a variation of 1.7-5.1 dBi for the projected operating range, resulting in a considerable sensitivity for application in the

PD detection. However, the developed PMA was not subjected to practical tests of PD detection.

In [45] is presented a PMA with elliptical geometry applied to its patch, developed for the PD detection in power transformers. The PMA was designed to operate in the frequency range of 1.2-3 GHz, resulting in dimensions of only 10 cm in length and 8 cm in width. In addition, the PMA developed by the authors showed an average gain of 2.39 dBi for the projected operating range. Despite the compact size and good gain results obtained, the PMA presented has an operating range that covers only a small portion of the main spectrum of PD activity, and may be insensitive to discharges that have a spectrum between 300 MHz-1.2 GHz. Furthermore, in the practical tests performed in laboratory by the authors, the PMA detected PD activity only for the distance of 25 cm, not being tested for greater distances commonly found in the practical monitoring of PD in power transformers.

In 2019, the applicability of a PMA with circular patch in the PD detection was evaluated in [46]. The antenna developed in [46] had an operating range that covers practically the whole spectrum of the main PD activity, with frequency values from 312-1481 MHz. The final dimensions of the antenna were 30 × 30 cm^2 and, during the measurements performed in laboratory, was able to detect PD with an apparent charge of 30 pC, representing a high detection sensitivity. In addition, based on an analysis of the frequency of the detected PD pulses, the authors verified the PD activity for different frequencies between 333 MHz and 1.21 GHz. Despite the efficiency presented by the PMA developed in [46], the final dimensions obtained make it more suitable for applications in the detection of PD in environments where there is greater flexibility of space for installation of the antennas, such as in the monitoring of high voltage equipment in open area substations. For applications in environments with dimensional restrictions, such as dielectric windows, for example, it is necessary to use miniaturization techniques.

A miniaturization of a PMA developed for the PD detection was presented in [47], in which the PMA geometry was bio-inspired based in the leaf of Inga Marginata, as illustrated in Fig. 6. The developed PMA had an operating range of 340 MHz up to values above 8 GHz, with final dimensions of 34 cm in length and 14 cm in width. In addition, the PMA average gain, measured for the operating range from 400-1500 MHz, was 3.63 dBi, providing sufficient sensitivity for the detection of PD pulses with an apparent charge of 65 pC, as shown during its measurements in laboratory. Finally, the PMA presented in [47] proved to be insensitive to detecting corona discharges, one of the main sources of interference in the application of the radiometric method, mainly in open area substations. Despite the compact dimensions presented, the bio-inspired PMA presented by the authors still has a relatively large size for applications in dielectric windows, so its use in open area substations is recommended due to its characteristic of omnidirectional radiation pattern and insensitivity to corona discharges, as highlighted by the authors in their work.

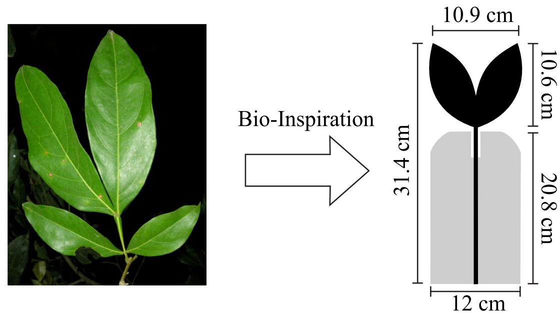

FIGURE 6. General view of the bio-inspiration process performed in [47].

A miniaturized PMA with geometry bio-inspired on the leaf of the Jatropha mollissima (Pohl) Baill plant was presented in [48] for the PD detection in power transformers. The final dimensions obtained for the bio-inspired PMA were 20 × 20 cm^2, resulting in an adequate size for application in dielectric windows of power transformers. The operating range of the developed PMA was 487-1497 MHz. In addition, in [48], the impact on the reflection coefficient and gain caused by the metallic and dielectric structures of a dielectric window was also evaluated for the developed PMA. In laboratory, the set composed by the bio-inspired PMA and metallic structure was sensitive to the detection of PD with 35 pC of apparent charge. Despite the successful results presented by the authors in [48], the gain measurements performed on the bio-inspired PMA demonstrated that the developed antenna presents an average gain of 2.92 dBi for its operating range, in which the gain values only exceed the value of 2 dBi from the frequency of 700 MHz. In this way, the sensitivity of the sensor can be affected for PD pulses located below this frequency. Therefore, it is necessary to apply gain optimization techniques to improve the sensitivity of the sensor in the PD detection.

The application of gain enhancement techniques in the design of UHF bio-inspired PMA sensors was explored in [49] in order to improve its PD detection sensitivity. For this purpose, the authors in [49] proposed the adaptation of dielectric windows through the application of metamaterial structures as dielectric superstrate. The metamaterial was obtained through the combination of nine split ring resonators (SRR) unit cells distributed over a FR4 dielectric superstrate. The results obtained demonstrated that the metamaterial superstrate insertion resulted in a mean gain enhancement of 0.7 dB regarding the reference PMA (without superstrate) evaluated, producing an antenna with better sensitivity for PD detection (mean gain of 3.61 dBi) due only to modifications on the high voltage dielectric window. In addition, the metamaterial superstrate did not impact the original bandwidth, covering most of the characteristic frequency range of PD activity. The developed PMA-metamaterial set was able to detect PD activity in an operating 230 kV current transformer (CT). After the online PD detection on CT, the equipment was conducted to laboratory in order to check the PD activity through IEC 60270 method, attesting that the UHF signals detected by the PMA-metamaterial set were, in fact, generated internally in the CT by the PD activity. Finally, the PD signals detected by the PMA-metamaterial set presented higher voltage levels than those simultaneously detected by the reference PMA, corroborating the sensitivity enhancement through the application of a metamaterial superstrate. The methodology for the metamaterial superstrate design and tests (laboratory and field) adopted in [49] is summarized in Fig. 7.

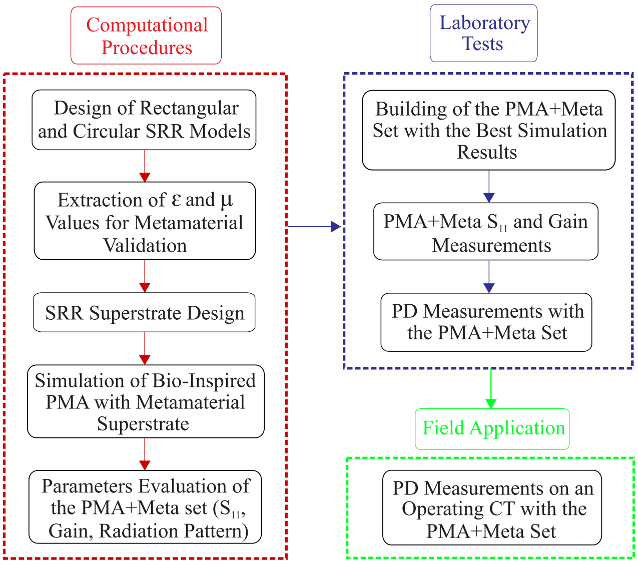

FIGURE 7. General flowchart of the procedures adopted in [49] for the application of bio-inspired PMA with metamaterial superstrate in PD detection.

In [50], it was developed an Archimedian spiral antenna for the PD detection in the frequency range of 600 MHz up to 1.7 GHz band. A balun was coupled to the antenna in order to perform the impedance matching between the antenna patch and the connection terminal (50 Ω), acting as an impedance transformer. As a differential, the authors applied the set consisting of the spiral antenna and the balun in a structure containing a superstrate and FR-4 substrate. However, the superstrate was inserted only in order to reduce the dimensions of the developed antenna, resulting in a structure with 190 mm in diameter and 153 mm in height. The built antenna presents results of measurement of reflection coefficient, radiation pattern and gain very close to the simulated and promising for the application in PD detection. However, the structure developed by the authors in [50] has not been subjected to practical tests of PD detection.

In Table 1, the contributions of the works cited are summarized. It is worth mentioning that the work carried out by the authors in [37] is not included in this summary table, since his contributions and analysis on the sensors were mostly mathematical, not fitting within the topics listed for the summary presented.

A. TRENDS, CHALLENGES AND OPEN ISSUES

Some works related to the development of UHF sensors, applied in the PD detection, were presented throughout this section. It can be observed that several publications have successfully addressed the use of planar antennas and other types in the detection of PD through dielectric windows, whether in power transformers or GIS. In addition, some of the developed works explored the use via drain valves of power transformers, despite the practical limitations for applications in the location of defects. However, many of the developed antennas presented fail to meet the entire frequency range of the main activity of PD (300-1500 MHz). The failure in to cover the range of the main PD activity can result in the generation of false negatives, since different defects in the insulation system (internal, surface, corona and others) can generate electromagnetic waves with higher concentrations of energy in different frequency bands inserted in the spectrum from 300-1500 MHz. Therefore, some defects may not be detected by the monitoring system in the case of antennas that do not have full coverage, or a large part, of the main range of PD activity, stimulating the search for alternative structures that allow broadband operation.

As shown, the broadband operation criterion was met from the application of PMA, which proved to be efficient in the detection of low intensity PD in the entire frequency range mentioned above. However, the PMA presented in most of the works discussed still had dimensional limitations that made them more appropriate for application in monitoring equipment in open area substations. In order to make PMA suitable, in dimensional terms, for applications in dielectric windows, more recent research has focused in the application of PMA miniaturization techniques using bio-inspired geometries, resulting in the development of compact UHF sensors with broad bandwidth and high PD detection sensitivity. Although the great potential application for PD monitoring, the use of bio-inspired PMAs in practice, in a real substation, has rarely been explored in the literature and is limited to superficial investigations as presented in [49].

Furthermore, it is also verified that few works in the literature explored the use of gain enhancement techniques in the design of UHF sensors applied in PD detection. The greater the sensor gain, the greater its detection sensitivity, allowing the PD detection in even more early stages, which significantly contributes to the asset management of an electric utility and optimizes the maintenance scheduling on monitored equipment. In addition, the development of even more sensitive UHF sensors also enables their use in laboratory tests for equipment commissioning before its application in substations, expanding the UHF method field of application.

Despite the potential of the UHF method, it is not yet possible to perform PD apparent charge calibrations from the antennas used, only real-time monitoring of PD activity evolution in the equipment is possible. Therefore, studies are still necessary in order to propose some methodology that facilitates the estimation of the PD apparent charge levels from the UHF signals detected by the applied antennas, whether PMA or any other type. For this, factors such as bandwidth; gain variation according to frequency; signal attenuation according to the distance (with and without obstacles) between

TABLE 1. Summary of works in the area of PD UHF detection sensors.

References	Operating Range (GHz)	Average Gain (dBi)	Dimensions (cm)	Geometry	Detected PD level (pC)	Tests	Type
[33]	0,03-1	–	–	Spiral	5000	Laboratory	Probe
[34]	0,34-0,44	5,38	34 × 20	Rectangular microstrip	232	Laboratory and field	Window
[35]	0.5-0.7	–	10 × 2,5	Conical	500	Laboratory	Probe
[36]	0.24-0.45	–	17 (diameter)	Log-espiral	–	Laboratory	Window
[38]	0.38-0.42	1,29	24,2 × 4,9	Microstrip dipole	–	Laboratory	Window
[39]	0,67-0,69; 0,88-0,92; 1,05-1,15 and 1,26-1,28	–	–	Planar monopole	50	Laboratory	Probe
[40]	0,3-1 (VSWR < 5)	10 (using a 40 dB amplifier)	10 × 10	Hilbert fractal	33,88	Laboratory	Window
[41]	0,12-0,8	–	70 × 64	Adapted rectangular PMA	–	–	External
[42]	0,7-1,5	3	19,18 (diameter)	Complex planar spiral	–	–	Window
[43]	0,5-1,5	2,32	25 × 20	Adapted rectangular PMA	2849	Laboratory and field	External
[84]	0,35-1,38	3,4	24 × 20	Adapted rectangular PMA	–	–	External
[45]	1,2-3	2,39	10 × 8	Eliptic PMA	5	Laboratory	Window
[46]	0,312 – 1,481	4,58	30 × 30	Circular PMA	30	Laboratory	External
[47]	0,34-8	3,63	34 × 14	Bioinspired PMA	65	Laboratory and field	External
[48]	0,487-1,497	2,92	20 × 20	Bioinspired PMA	35	Laboratory	Window
[49]	0,543-1,519	3,61	20 × 20	Bioinspired PMA with metamaterial superstrate	15	Laboratory and field	Window
[50]	0,6-1,7	4	19 (diameter)	Spiral *Archimedian*	–	–	Internal

the antenna and the PD source; and others factors should be considered in order to generate compensation curves that can assist in the signal amplitude recovery, revealing a value closer to the real intensity (pC) of the PD activity internal to the monitored equipment.

Finally, from the continuous monitoring of the PD activity evolution in high voltage equipment through UHF sensors, it is possible to evaluate in future studies the possibility of equipment lifetime estimation from the application of techniques such as time series and other prediction methods [51]–[56] to collaborate in the decision making process by maintenance teams.

Therefore, the trends, challenges and open issues related to studies in the UHF sensor development search area can be summarized as follows:

- Sensor miniaturization;
- Wideband sensors development;
- Gain enhancement (sensitivity improvement) techniques application;
- Sensor calibration;
- Failure prediction.

III. CLASSIFICATION OF PD SOURCES FROM IEC 60270 METHOD IN HIGH VOLTAGE EQUIPMENT

As previously mentioned, the use of the IEC 60270 standard is one of the most efficient and consolidated method for PD quantification. In addition to the PD detection, it is also possible, using the IEC 60270 method, to identify different patterns of defects, that is, different types of PD, such as superficial, internal or corona discharges, for example. This can assist on the assertiveness of maintenance teams (in conjunction with location algorithms) and in the identification of the defect severity, since internal discharges can represent a greater destructive potential than corona discharges, for example. Furthermore, from the classification techniques it is also possible to identify the number of defects existing in high voltage equipment, providing a complete diagnosis. Therefore, the IEC 60270 method has been applied for defect classification purposes since the late 1980s, currently serving as a comparative method for the development of new classification methodologies using less invasive and online techniques, such as the UHF method. Thus, in this section, a brief historical review regarding the application of the IEC 60270 method in the classification of defects is presented in order to better understand the parameters and techniques currently applied in conjunction with the UHF method for PD classification.

In 1988, the first methodology for PD classification based on the visual identification of patterns was described by Nattrass [57]. For this, it was presented several sets of insulations with defects and correlated them with some characteristics related to the PD activity, such as: voltage at the start of activity (PD inception), intensity, duration and location in time (phase). However, since the procedures were based on a visual classification, the methodology proposed in [57] was strongly dependent on the specialist experience, which became a limitation for the diagnosis of high voltage equipment.

After verifying the limitations of the PD signals visual classification, a computational system for the PD analysis was developed by Gulski and Kreuger [58]. The analysis was made from the combination of statistical parameters and characteristics extracted from the signals acquired in the laboratory through IEC 60270 method. The characteristics extracted from the signals are defined as basic quantities, and correspond to the main parameters observed in [57], i. e., inception voltage, pulse intensity and its position in relation to the phase of the applied voltage. The statistical parameters were denominated by the authors as ''deducted quantities''. The deducted quantities are basically a complement to the basic quantities, providing more detailed information from the observation of the PD activity in a time window much greater than the period of the applied voltage (a few hundred or thousands of cycles).

The main statistical parameters considered in [58] are: pulse count ($H_n(\phi)$), mean amplitude ($H_{qn}(\phi)$) and peak values ($H_{qi(\text{peak})}(\phi)$). The $H_n(\phi)$ distribution represents the number of discharges observed in each phase window as a function of the phase angle, while the $H_{qn}(\phi)$ and $H_{qi(peak)}(\phi)$ distributions provide information regarding the mean intensity and peak values, respectively, for each evaluated phase window. From the combination of these three distributions, it is possible to distinguish between noise and discharge, as well as to characterize the severity and type of discharges from the analyzed distributions with greater independence from the operator's subjectivity.

The statistical distributions evaluated in [58] can be graphically summarized through the phase resolved partial discharge (PRPD) analysis, from which, still in 1992, it is demonstrated in [59] that it is possible to obtain the identification of characteristic PD patterns, as illustrated in Fig. 8.

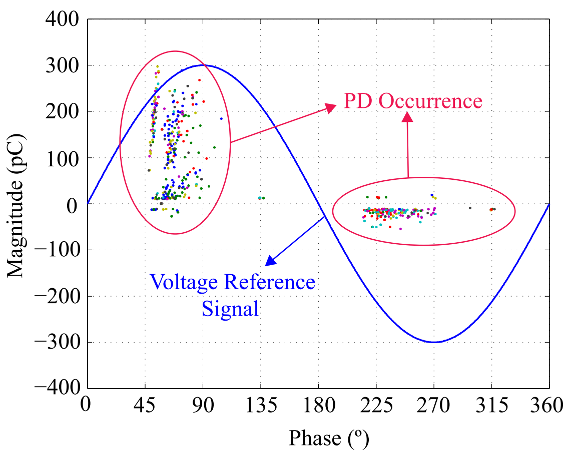

FIGURE 8. PRPD pattern example.

In order to automate the PD defect classification process, works such as those developed in [60]–[62] applied the data referring to the PRPD statistical parameters as input of artificial neural networks (ANN). In [63], it is shown that the classification method based on automatic decision obtained a hit rate of 75%, while, for the same database, a group of consulted experts obtained a hit rate of approximately 30%.

After consolidating the efficiency of the IEC 60270 method to detect and identify PD patterns in defective insulations, in the subsequent years, the works had as main objective the optimization of the method, searching the addition of new statistical parameters, such as voltage difference between two consecutive pulses [64], kurtosis, asymmetry and cross correlation factor [65]; and the application of alternative techniques such as wavelet transform (WT) [66] and Weibull distribution [67], for the increase of the success hit rates. In addition, other classification tools were evaluated, such as fuzzy logic [68] and support vector machine (SVM) [69].

Despite the efficiency of the IEC 60270 method and PRPD analysis, the practical limitations mentioned at the Section I for application in continuous field monitoring have encouraged researchers to seek alternative methods of PD measurement that have detection and classification efficiency comparable to the conventional method. Therefore, the IEC 60270 method and PRPD analysis have become consolidated comparative references for the analysis of new methodologies regarding the PD detection sensitivity and the identification of different PD patterns.

In the next section, some works that used the UHF method to identify different types of PD in high voltage equipment are presented.

IV. PD SOURCE CLASSIFICATION IN HIGH VOLTAGE EQUIPMENT BY USING THE UHF METHOD

In [70], using envelope comparison of UHF PD signals, it is verified that is possible to differentiate whether PD events originate from the same or different sources. The technique exploits the fact that the envelope of a UHF signal contains features that are ruled by the relative positions of the signal source and sensor in the high voltage equipment under monitoring. By rectifying and smoothing the UHF signal using a simple RF circuit, the characteristic shape of the envelope is produced. PD sources at different locations are differentiated using a mathematical measure of the difference between their normalized envelopes. The smaller the difference, the greater the similarity between the signals. For the experiment performed in [70], envelopes with a difference lower than 2.3 are considered similar (same source), while envelopes with differences greater than 2.3 are considered as coming from different defect sources. However, the authors highlighted that the values of the mathematical differences adopted are valid only for the experiment carried out in their work and that, for the replicability of the proposed methodology, it is necessary to establish appropriate mathematical difference thresholds for new set of defects.

In 2011, the authors in [71] performed the classification of five types of common defects in a GIS: floating metal, protrusion, bouncing particle, cavity between spacers and surface discharges in insulating materials. For each of the aforementioned defects, PRPD standards, generated by the IEC 60270 method, and a database of PD pulses, captured by an internal UHF sensor, are obtained for a 220 kV GIS. From the detected pulses, nine analysis parameters are extracted to separate the defects into five clusters. Three of the extracted parameters are related to the information regarding the amplitude of the pulses detected by the UHF sensor, such as, the mean magnitude (E_{mag}), the total number of discharges (N_{mag}), and the standard deviation of magnitude (S_{mag}). Three other parameters are related to the time intervals between one pulse and another, also using the mean (E_{int}), total number (N_{int}) and standard deviation (S_{int}) for the extraction process. The three remaining parameters are related to the intermission between discharges (ΔT_{mean}), discharge polarity (P) and discharge distribution ($N_{\text{reg.}}$). From the application of the nine parameters aforementioned in a K-means analysis, an overall success rate of 96.6% is obtained.

To evaluate the applicability of the UHF method for classification purposes in power transformers, in [72], it is applied a UHF probe via an oil valve in a 120 MVA transformer with fifty years of operation. To prove the efficiency of the method, comparative measurements with the IEC 60270 method and PRPD analyzes are carried out during three years of observation of the equipment. At the end of the experiment, it is found that the UHF method is efficient in the detection of internal discharges present in the transformer, as well as in the classification of the three defects, previously identified through PRPD analysis, based on statistical parameters related to the mean and maximum amplitude, as well the repetition rate and standard deviation.

In [73], spectral power analyzes of PD pulses and spectral power ratios at different frequencies are calculated to classify PD sources and noise by means of a graphical representation in a plane. Two power ratio quantities are obtained, one for high frequencies (5-15 MHz), described as power ratio high (PRH), and another for low frequencies (15-25 MHz), described as power ratio low (PRL). Using these parameters, pulse source identification is verified for the three typical types of PD sources: corona, surface discharge and internal. For all the test objects evaluated in [73], the use of the power ratio resulted in clearly different clusters for noise and discharges. In addition, each type of PD source leads to either a cluster located at a different position or with a different shape in the power ratio map, assisting in the parameter extraction for the automatic classification. Although the frequency range evaluated is lower than the UHF, the methodology presented in [73] is a flexible technique because the frequency intervals can be changed on-line depending on the observed spectral range, making possible the adaptation for the application at the UHF range, as presented later in [74], in which a method of PD source separation and classification is proposed using the power ratio maps applied in [73] and PD signals detected by UHF antennas. The PRL and PRH ranges evaluated in [74] are equal, respectively, to 50-300 MHz and 600-1600 MHz.

In [75] is presented the application of the adaptive optimal kernel (AOK) method, aided by non-negative matrix factorization and principal component analysis (NMF-PCA), for the extraction of time-frequency parameters for the classification of UHF signals from four different sources of defects emulated from distinctive electrode configurations, namely: cavity discharges, surface discharges in insulating oil, discharges of floating particles on the insulating oil and corona discharges in insulating oil. Based on the proposed methodology, hit rates of up to 94.33% are achieved.

Various electrode configuration was also used in [76] to emulate some defects, such as: corona discharges in insulating oil, surface discharges and internal-type discharges (cavities). The PD signals are captured by a fractal UHF antenna. The extraction parameters are based on the frequency of PD occurrence originated by each defect created in the laboratory. After inserting the frequency parameters as input for the K-nearest neighbors (KNN) method, a 95% hit rate is achieved for the aforementioned defects.

A PD separation algorithm based on the cumulative energy function is presented in [77]. Four typical PD defects (surface, internal, protrusion and free particle discharges) are considered and multiple source experiments are performed to gather waveforms from different PD groups. The time-domain and frequency-domain cumulative energy functions are calculated from the PD waveforms and their FFT spectra, respectively. In addition, from the mathematical morphology gradient (MMG) operation, sharpness features are extracted to characterize the upward slope of the cumulative energy curve. From the MMG and the cumulative energy curves, width, sharpness and gravity parameters are extracted in both the time and frequency domains, resulting in a feature space with six dimensions. For the identification of clusters in the resulting feature space, the improved density-based spatial clustering of applications with noise (IDBSCAN) is applied. The separation algorithm is examined with the PD mixed pulses acquired during the experiments and the results proved the feasibility of the separation algorithm with different PD defects. The algorithm developed in [77] can be summarized by the flowchart presented in Fig. 9. Although the validation of the proposed algorithm was made using the IEC 60270 method, the methodology presented in [77] is a flexible technique that can be easily adapted for UHF PD monitoring applications, as presented later in [78], in which the algorithm showed itself effective for the classification and separation of mixed UHF PD signals.

A comparison between the PRPD graphs generated from PD measurements in power transformers using the IEC 60270 and UHF methods is made in [79]. For this purpose, three types of defect are created in laboratory: corona discharges in air, surface and internal discharges. Each of the aforementioned defects is inserted into a representative model of a power transformer tank and subjected to simultaneous PD measurements using the IEC 60270 and UHF methods. The results presented demonstrated a considerable similarity between the PRPD generated by both methods for each of the

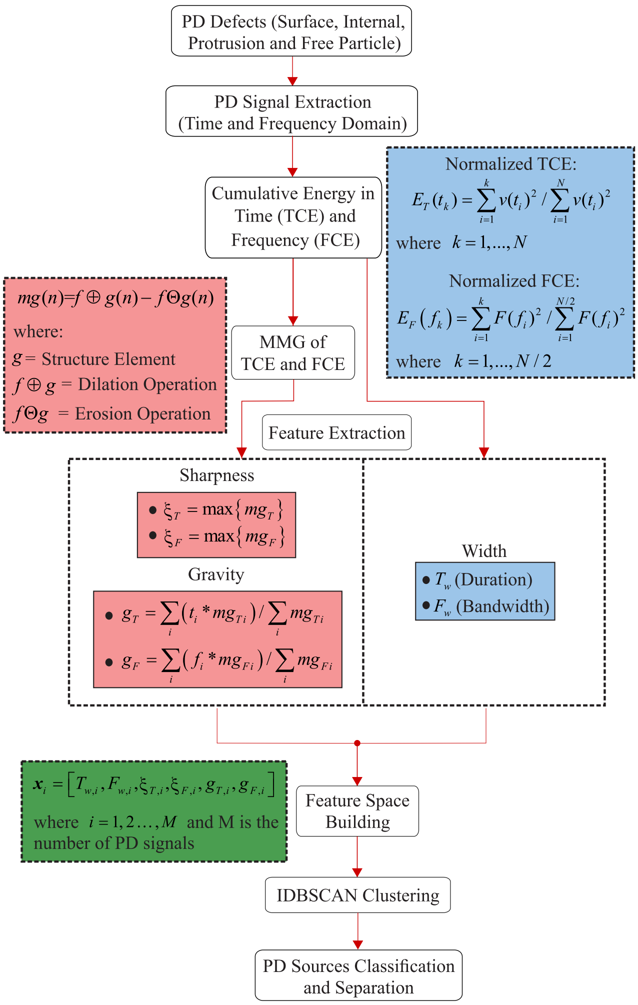

FIGURE 9. Flowchart of the PD classification and separation algorithm developed in [77].

defects emulated in laboratory. However, the PRPD patterns generated for the UHF method showed significant changes according to the detection sensitivity of the applied sensor and the distance at which the defect is positioned inside the transformer tank.

In [80] it is evaluated the extraction of features concerning the time and frequency domain for the classification of PD UHF signals from three defect sources immersed in insulating oil: corona, surface discharge and moving particles. The feature extracted in the time domain refers to the calculation of the PD pulse duration (T), which is performed by determining the width of the probability distribution function (PDF) based on its second central moment. For the frequency domain, the bandwidth (W) values of the PD pulses are obtained. In addition to the values of T and W, the absolute maximum value of derivative of the UHF signal (D) is also considered as one of the features for the PD classification. The three features (T, W and D) are applied as input of a quadratic SVM, resulting in average hit rates of 99.14% with UHF sensor positioned 1 m away from the defect sources encapsulated in a metal tank.

In addition to the classical statistical parameters used for the classification of PD signals (skewness, kurtosis and other aforementioned), the use high-order moments and entropy histograms of the PD pulses as input features in SVM classifiers and neural network with back propagation (BP) was evaluated in [81]. The features are extracted from UHF signals generated by defect cells, inserted into a GIS in laboratory, which represent discharges such as: corona, surface, internal and suspension particles. From the selected features, hit rates of 81.25% and 80% are obtained for the SVM and BP neural network classifiers, respectively. In addition, it was also verified the hit rate resulting from entering the same extracted features as input into a mixed classifier (SVM plus BP), resulting in an accuracy of 90%, representing an improvement of approximately 10% in comparison with the individual use of the aforementioned classifiers.

In [82], only phase and amplitude (PA) data from PRPD graphics were used as input parameters of a convolutional neural network (CNN) in order to classify six types of defects in power transformers: protruding electrode, particle, floating, surface, bad contact between windings and void. The defects are emulated from artificial cells created in laboratory, whose PD signals are detected by a monopole UHF antenna with a frequency range of 300-1800 MHz and designed for application as a drain valve UHF sensor. For comparative purposes, CNN is compared with other types of classifiers, namely linear SVM, nonlinear SVM with radial basis function (RBF) and feedforward neural network (FNN), all using PA features as input. The CNN proposed by [82] resulted in an overall hit rate of 99.64%, against the overall rates of 90.88%, 88.69% and 80.66% obtained, respectively, by the linear SVM, nonlinear SVM with RBF and FNN classifiers.

In [83], it is proposed the multi-feature combination adaptive boost classification model to build an optimized classifier, capable of identifying seven types of defects in high voltage equipment insulation systems, namely: suspending electrode, metal protrusion on the enclosure and conductor, metal particles contamination on the spacer, metal contamination on the spacer, a void in the insulator and free metal particles on the enclosure. The PD pulses generated by each of the aforementioned defects were detected from a UHF sensor with a frequency range of 500-1500 MHz. The PD pulses detected by the UHF sensor are represented by means of three distinct visualization patterns: the classic PRPD format; the phase resolved pulse sequence analysis (PRPSA) and; polar coordinate phase resolve analysis (PCPRA). From each of PD pattern representations, it is possible to extract different features that can be used as input parameters of a classifier. Based on the algorithm proposed by the authors, the best combination of features from each representation pattern is evaluated to obtain the best hit rate. In addition to selecting the best combination of features, the model proposed by [83] also selects an optimal classifier from the combination of several base classifiers, in this case different types of SVM

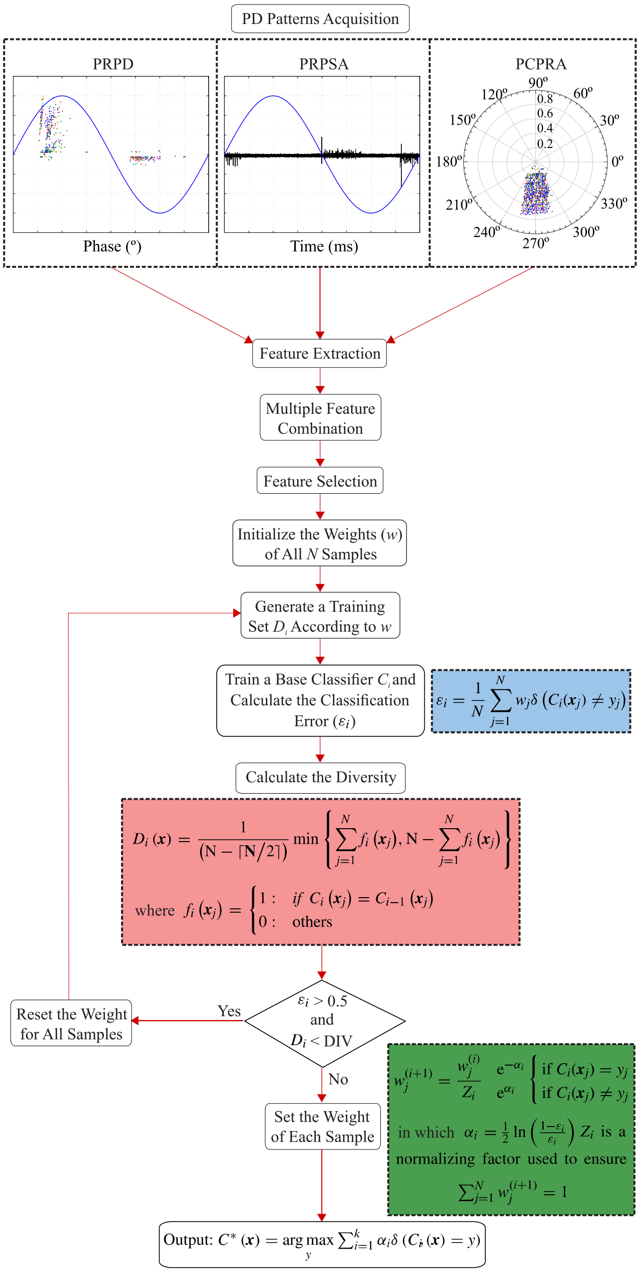

FIGURE 10. Flowchart of the multi-feature combination adaptive boost classification model proposed in [83].

classifiers. From the proposed methodology, the authors verified that the best combination of features is obtained from the union of the three forms of representation and using a Gaussian kernel function. The SVM resulting from the adopted methodology presented an overall hit rate of 90%, higher than the rates obtained by other classifiers evaluated by the authors for comparative purposes, namely: back propagation neural network (82.08%), radial basis function neural network (82.08%), K-nearest neighbor (77.50%) and, classification and regression tree (70.83%). The flowchart summarizing the main steps of the multi-feature combination adaptive boost classification model proposed in [83] is presented in Fig. 10.

A. TRENDS, CHALLENGES AND OPEN ISSUES

According to the literature review carried out in this section, it can be seen that several publications were successful in classifying various types of defects created in laboratory and detected using the UHF method, reaching success rates above 90% in many of the studies evaluated. It can be verified that, although new features have been explored over the years, the use of classical statistical parameters applied in the PRPD analysis is still considered a good basis for the development of PD classifiers. Thus, one of the main objectives of the works developed in this area in recent years is the improvement of the developed classifiers, many of them, seeking the combined application of classical classifiers, such as ANN, SVM, decision trees and fuzzy based classifiers [84], [85].

Due to the advances in the signal processing area and data acquisition instruments, large amounts of information can be acquired and processed in modern monitoring systems. Therefore, in addition to the combination of classifiers, current research has sought to extract the best hit rates of classifiers from the development of algorithms for optimal combination of different input features, which can be obtained from PRPD, PRPSA [86], PCPRA [87] graphics or through further analysis of the detected PD UHF signals [83], [88]. For the proper separation or dimensional reduction of the various features that can be extracted from UHF PD signals, methods such as independent component analysis (ICA) and principal component analysis (PCA) can be used for this purpose [32]. Furthermore, technological advances in signal processing and acquisition methodologies have also provided the development of several works that make use of deep learning techniques for pattern recognition in various fields of study, such as image classification, segmentation, detection and tracking [89], [90] with hit rates usually higher than other classic machine learning approaches. However, the deep learning is still little explored in the area of PD detection [82], [91]–[96] mainly due to the higher computational processing time compared to the classical approaches used by the papers described throughout this article. Therefore, further studies regarding the feasibility evaluation of the application of deep learning techniques in the recognition of PD patterns are still needed, aiming to find classifiers that present high hit rates based on, desirably, a relatively low computational cost and a small number of input features.

From the evaluated works, it can be verified that the use of classifiers is applied not only for the identification of defects but also for their separation in the case of multiple sources. During atmospheric and switching surges, or in the occurrence of faults in general, there is the possibility of damage to several areas of the insulating system of the high voltage equipment, which can lead to the origin of different multiple defects in the same equipment. The existence of multiple defects in an equipment can make it difficult to apply location algorithms based on TDOA, since there is a high probability of signal superposition. Therefore, it is necessary to develop even more robust classifiers capable of identifying the type and number of defects in high voltage equipment,

TABLE 2. Summary of work in the area of PD classification and their respective contributions.

Reference	Contribution	Classifiers	Features	Hit Rate (%)
[70]	Verified that is possible to differentiate whether PD events originate from the same or different sources using envelope comparison of UHF PD signals.	-	Difference between normalized envelopes (D)	-
[71]	Performed the classification of five types of common defects in a GIS through PRPD standards, generated by the IEC 60270 method, and a database of PD pulses, captured by an internal UHF sensor.	K-means	E_{mag}, N_{mag}, S_{mag}, E_{int}, N_{int} S_{int}, ΔT_{mean}, P and $N_{\text{reg.}}$	96.6%
[72]	Evaluated the applicability of the UHF method for classification purposes in power transformers through an UHF probe via drain valve in a 120 MVA transformer with fifty years of operation.	PRPD Analysis	Mean and Maximum Amplitude, Repetition Rate and Standard Deviation	-
[74]	Proposed a method of PD source separation and classification the power ratio maps applied in [73] and PD signals detected by UHF antennas.	Power Ratio Map	PRL and PRH	-
[75]	Presented the application of the AOK method, aided by NMF-PCA, for the extraction of time-frequency parameters for the classification of UHF signals from four different sources of defects emulated from distinctive electrode configurations.	Fuzzy k-nearest neighbor	Time-Frequency Parameters	99.33%
[76]	Used a fractal UHF antenna to capture defects emulated by various electrode configurations, namely: corona discharges in insulating oil, surface discharges and internal-type discharges (cavities).	KNN	PD frequency of occurrence	95%
[77]	Presented a PD separation algorithm based on the cumulative energy function. Time-domain and frequency-domain cumulative energy functions are calculated from the PD waveforms and their FFT spectra, respectively. In addition, from MMG operation, features were extracted to characterize the upward slope of the cumulative energy curve.	IDBSCAN	Width, Sharpness and Gravity (all of them in time and frequency domains)	-
[79]	Made a comparison between the PRPD graphs generated from PD measurements in power transformers using the IEC 60270 and UHF methods.	PRPD Analysis	-	-
[80]	Evaluated the extraction of features concerning the time and frequency domain for the classification of PD UHF signals from three defect sources immersed in insulating oil with UHF sensor positioned 1 m away from the defect sources encapsulated in a metal tank.	Quadratic SVM	PD pulse duration (T), Bandwidth (W) and Maximum Derivative (D)	99.14%
[81]	Used high-order moments and entropy histograms of the PD pulses in addition to the classical statistical parameters used for the classification of PD signals. In addition, the authors also proposed the combination of two classifiers (SVM plus BP) in order to improve the classification hit rate. used as input features in SVM classifiers and neural network with back propagation (BP).	SVM plus BP	High-Order Moments, Entropy Histograms and Classical PRPD parameters	90%
[82]	Used only PA data from PRPD graphics as input parameters of a CNN in order to classify six types of defects in power transformers emulated from artificial cells created in laboratory.	CNN	PA	99.64%
[83]	Proposed the multi-feature combination adaptive boost classification model to build an optimized classifier, capable of identifying seven types of defects in high voltage equipment insulation systems. The PD pulses detected by the applied UHF sensor are represented by means of three distinct visualization patterns: the classic PRPD format; PRPSA and; PCPRA. Based on the algorithm proposed by the authors, the best combination of features from each representation pattern is evaluated to obtain the best hit rate and classifier.	SVM	PRPD, PRPSA And PCPRA features	90%

serving as a support tool for the more efficient application of location algorithms, optimizing the management of assets of electricity utilities and making the work of maintenance teams even more assertive.

Therefore, the trends, challenges and open issues related to studies in PD source classification in high voltage equipment by using the UHF method can be summarized as follows:

- Classifiers combination;
- Development of optimal feature combination algorithms;
- Deep learning applications;
- Multi-source signal separation classifiers.

V. LOCATION OF PD SOURCES IN HIGH VOLTAGE EQUIPMENT

In 2006, the cross correlation method was applied in [97] to assist in the process of extracting the arrival time instants for the PD location in power transformers. In addition, the genetic algorithm was also applied. To validate the method, a single-phase transformer model in laboratory, PD generating cells and four monopole antennas with a bandwidth of 1-5 GHz were used. The antennas were 2 cm length and were spaced 30 cm apart in a diamond type arrangement in which the acute angle had an opening of 60 degrees. The results demonstrated the efficiency of the method, resulting in a location error of only 16 cm.

In [98], it was evaluated the efficiency of the discrete wavelet transform (DWT), as a noise filtering technique, in the extraction and determination of the arrival time instants of UHF signals. The results obtained by the authors demonstrated that the extraction of the PD signal from the DWT is efficient when the noise standard deviation is lower than the maximum amplitude of the PD UHF signal. Otherwise, the efficiency of DWT in signal extraction is significantly reduced. In addition, according to the authors, the mother wavelet that produces the best results for the extraction of PD signals is the Daubechies with 11 levels of decomposition, as it presents waveforms quite similar to the UHF responses for PD pulses. Despite the efficiency in noise rejection, the use of DWT resulted in small impacts in the determination of the arrival time instants, causing differences of up to 0.6 ns, which may result in location errors of up to 18 cm due only to the filtering technique noise adopted.

Three methods for the TDOA extraction were analyzed in [99] for the purpose of PD location, namely: first peak, cumulative energy and cross correlation. The TDOA principle of calculation for each of the aforementioned methods is presented in Fig. 11. For all the evaluated methods, the WT was applied as tool for noise filtering. For the cross correlation method, in addition to the WT, the cubic splines interpolation was used in order to improve the TDOA extraction precision. The authors justified that the use of this type of interpolation is necessary for the case of signals with low sampling rate. As highlighted in [98], it is also reported in [99] that the use of filtering techniques can result in small differences in the determination of arrival time instants due to little displacements in the first peak and in the knee point caused by the WT application, resulting in location errors that can be significant. According to the authors in [99], the best precision in determining the TDOA was obtained through the application of the cross correlation method. However, it is highlighted that the effective application of the method is dependent on the levels of the correlation coefficients obtained for the signals, in which the values of the coefficients must be greater than 0.8. Otherwise, the method will not be sufficiently accurate for the proper TDOA extraction. Therefore, the application of the cross correlation method in practice is quite limited, since the signals in field situations are subjected to attenuations, reflections, diffractions and refractions during their propagation, mainly, in the presence of obstacles (such as transformers windings, equipment and other structures distributed at the substation), resulting in the acquisition of distinct signals for each of the sensors used for location and, consequently, in low values of correlation coefficients.

In 2009, a system for locating defective equipment in open area substations based on the monitoring of PD activity was developed in [100]. For this purpose, four discone antennas with an operating range of 10-1000 MHz were used. The antennas were positioned at the roof of the control room building of two substations, one of 400/275/132 kV, located in the south of England, and the other of 69 kV, located in the eastern United States of America. The main objective in [100] was only the identification of which equipment had a defective insulation system. Therefore, the location of the PD source was carried out only in the 2D plane. Thus, the cross correlation method was sufficient to perform the location of the sources of defects. However, just like in [99], signal interpolation techniques were applied to improve the accuracy of the method. In addition, the authors in [100] also carried out studies on signal attenuation at various points in the evaluated substations in order to improve the estimation of the defective equipment location. The monitoring system

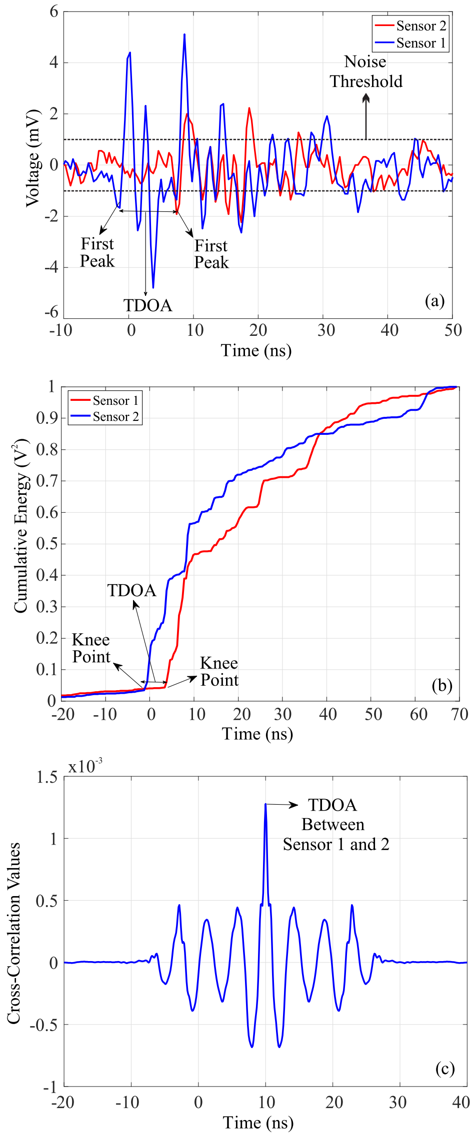

FIGURE 11. Principle of TDOA extraction for the (a) first peak, (b) cumulative energy and (c) cross-correlation methods.

developed in [100] was tested in the mentioned substations during the period of one year, resulting in the identification of suspicious PD activity in a 132 kV current transformer three weeks before the failure occurrence. For the 69 kV substation, the system also identified suspicious PD activity in one of the substation transformers, which was posteriorly subjected to power factor tests that confirmed the existence of a defect in its insulation system.

A technique for identifying multiple sources of PD from the comparison of the signal envelope obtained by the UHF sensor was proposed in [70]. For this purpose, the authors performed the analogical detection of the UHF signal envelope instead of the complete signal. In this way, the bandwidth and the sampling rate required to carry out the signal acquisition are significantly reduced. Then, the envelopes of the measured signals are compared in order to identify differences that indicate more than one source of PD. Although the method has the advantage of reducing the sampling rate required to acquire the UHF signal, one of the problems with the method is the loss of accurate information on the arrival time instant of the UHF signal. As consequence, the location of PD sources based on TDOA also becomes inaccurate.

The particle swarm optimization (PSO) technique was applied in [101] to improve the efficiency of the location results using the radiometric method. For this purpose, it was used a transformer tank model containing windings and a PD source composed by an automotive spark gap with a spacing of 1 mm. To detect the emulated PD, four UHF sensors were distributed around the tank. In addition, it was evaluated the PSO application considering various degrees of delay in calculating TDOA due to the presence of obstacles (windings) during the electromagnetic wave propagation. The degrees of delay were synthesized in a penalty term λ, ranging from 0 to 1, which was inserted in the objective function used in the PSO to minimize the location error. For all evaluated cases (six PD source positions), a population of 50 particles trained for 100 generations and with an inertia weight of 0.5 was used. The results presented in [101] demonstrated that smaller errors of location were obtained when considering $\lambda \geq 0.7$, presenting quadratic errors below 0.1236. Despite the good location results, the authors point out that there was not an optimal value of λ that would always define the best location results and that, therefore, it is necessary to carry out more in-depth studies that seek to relate the geometry of the equipment tank (and its windings) with propagation delays in practice, resulting in more accurate λ definitions.

In [102], it was carried out a comparative experiment using the main three methods for arrival time instant determination, namely: first peak, cross correlation and cumulative energy. As test object, it was a distribution transformer tank without the core and windings, in addition to being filled with only half of its oil capacity. The dimensions of the tank were 71.5 cm width, 118 cm length and 95 cm height. Four monopole antennas were distributed along the tank and the defect cell, composed of a tip-flat arrangement, was displaced in a spatial matrix with 12 different positions. For each defect position, 50 measurements of the signals obtained by each sensor were performed, resulting in an extensive database applied for the analysis of each of the arrival time extraction techniques. According to the authors in [102], the method that resulted in the obtaining of the best TDOA results was the first peak, with a location error of only 14.33 cm against 22.11 and 28.84 cm location errors obtained from the methods cross correlation and cumulative energy, respectively.

According to the work described in [103], the use of first peak detection, cross correlation and cumulative energy techniques are not sufficient to provide a precise location in noisy environments, such as open area substations. Thus, the use of statistical models such as four-order-cumulant and bispectrum was proposed to assist in the determination of the arrival time instants. To validate the efficiency of the proposed method, experimental tests were carried out in a 500 kV substation. For this purpose, four omnidirectional antennas with a bandwidth of 200 MHz-6 GHz were used jointly with 30 dB amplifiers in an operating range compatible with the applied antennas. A flat-tip arrangement was used as a PD generating cell, from which the authors obtained pulses with a frequency spectrum between 0-2 GHz and with an average rise time of 0.8 ns. From the proposed model, an error in the TDOA of 0.15 ns was obtained, which resulted in a location error of only 24 cm. When applying the cumulative energy method to the same set of signals evaluated, a significantly larger location error (1.73 m) was obtained, validating the efficiency of the application of the proposed statistical methods.

In 2014, PD location tests on a 120 MVA and 35/220 kV power transformer were performed in [104]. For this purpose, a defect in two phases of the high voltage winding was inserted, completely filled with oil. For the PD source location, four UHF sensors were used. The main contribution of [104] is the realization of tests with a real transformer in the laboratory, allowing the precise comparison between the real position of the defect and the estimation of its location, which was carried out in conjunction with computational simulations of reflections and refractions of the signals according to the geometric model of the transformer. However, the UHF sensors were positioned close to the produced defects, resulting in low impacts on the amplitudes and waveforms of the signals due to the phenomena of reflection, refraction, diffraction and attenuation. Therefore, consequently, low location errors (of the order of 10 cm) were obtained. Therefore, despite the good location results, it is necessary to carry out additional measurements that contemplate the positioning of the sensors at greater distances from the PD source, as well as with the presence of a greater number of obstacles between the PD source and the sensors to certify the algorithm location efficiency and reproducibility of the electromagnetic phenomena observed via simulations.

In 2015, an empirical method for verifying the optimum positioning of sensors in transformers was proposed in [105]. The method consists of computational tests of several arrangements, with the choice of the one that minimizes the location error in most cases of different defect positions. To prove the efficiency of the proposed method, four monopole antennas were used jointly with 20 dB amplifiers, installed in a 27 MVA (132 kV/11.5 kV) power transformer according to the optimal position obtained from the method proposed. The artificial PD generating cell was inserted at the position of 470 × 32 × 149 cm^3 and the position estimated by the location method adopted (similar to that applied by the authors in [23]) was 479×57×149 cm^3, resulting in a location error of 30.7 cm. According to the authors, location errors are minimized when the antennas are positioned with a maximum spatial distance between them and avoiding geometric positioning on the same plane. The optimum positioning algorithm steps proposed in [105] are presented in Fig. 12.

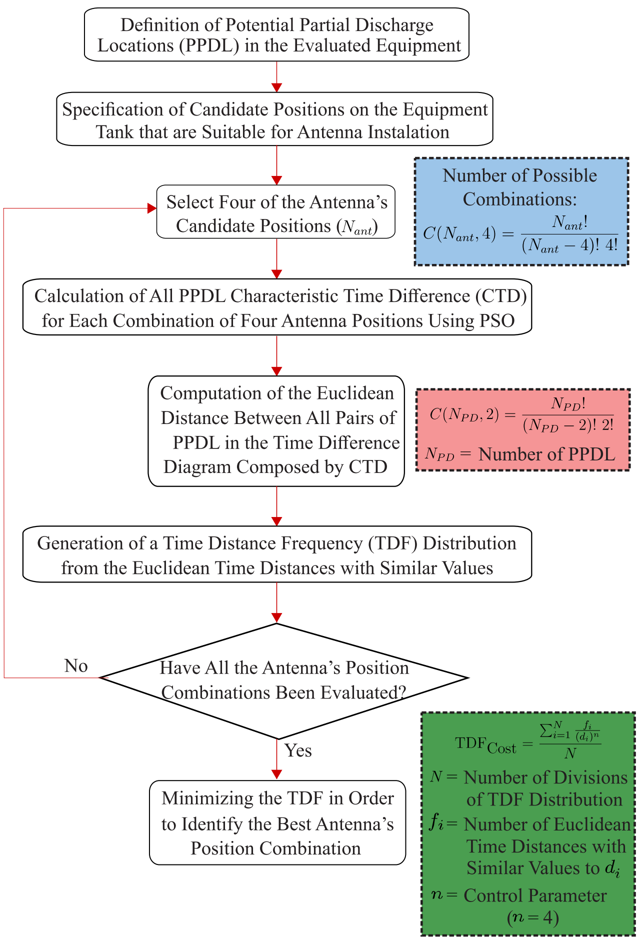

FIGURE 12. Flowchart of the optimum positioning algorithm proposed in [105].

The applicability of the radiometric method in conjunction with the TDOA for the location of defects in bushings of power transformers was evaluated in [106]. Four equiangular spiral antennas with a bandwidth of 2-6 GHz that were distributed in a T shape around a 126 kV bushing. As in [105], the antennas were positioned so that they were not located on the same geometric plane. It was performed the acquisition of 500 PD signals detected by the arrangement for each defect positioned in the bushing, in which the location errors outside the bushing were only 20 cm for a distance of 4.64 m between the antenna array and the defect, representing a satisfactory location result. However, the arrangement was not efficient in locating defects inside the bushing. The authors in [106] attribute the error of location of internal defects to the phenomena of propagation of electromagnetic waves (reflection and refraction), disregarded in their location algorithm. Finally, the antenna array was applied at the Ruibao substation (220/110/10 kV), in which the presence of PD was detected at the phase C bushing terminal of a power transformer. The result was confirmed by using an high frequency current transformer (HFCT) installed in the defective phase.

Unlike the other works referenced in this section, the application of rectangular microstrip antennas instead of monopole antennas was proposed in [107] for the separation of multiple sources and the location of defects in laboratory and in open area distribution substations. The TDOA algorithm was applied in conjunction with a Gaussian mixture model (GMM) and the first peak method. The accuracy of the proposed method to identify the number of sources was 94.9% and 90.7% for the tests carried out in laboratory and in field, respectively. The application of the proposed method resulted in location errors of approximately 1.4%. The results obtained in [107] highlighted the potential of application of microstrip antennas for the purpose of PD location using the UHF method, which until then had not been addressed in the literature. Despite the efficiency of the application of microstrip antennas in the location of defects presented in [107], the use of this type of antenna falls into practical limitations already discussed during the Section II, such as its narrow bandwidth, which may result in lower detection sensitivities for certain frequencies and, consequently, increasing the errors in locating defect sources. Therefore, it is still necessary to investigate the joint applicability between antennas with higher bandwidth (PMA) and algorithms of defect source location. The flowchart of the methodology proposed in [107] for PD location and multiple source separation using GMM is presented in Fig. 13.

Like [103], in [108] is described that the use of first peak detection, cross correlation and cumulative energy techniques are not sufficient to provide an accurate location in noisy environments. However, unlike [103], it is proposed a new model to assist in estimating the arrival time instants in power transformers filled with vegetable oil. The proposed model consists of the application of the cross recurrence plot (CRP) technique to support the definition of TDOA. To validate the proposed model, a cell filled with vegetable oil and with different configurations of immersed electrodes was used for the PD generation. The PD generating cell was placed inside a cubic spatial arrangement with 2.4 m length in each of its dimensions. Four spiral antennas with a gain of 3-6 dBi within the UHF operating range (300-3000 MHz) were distributed at the described spatial arrangement and used for the acquisition of PD signals from the oil tank. From the

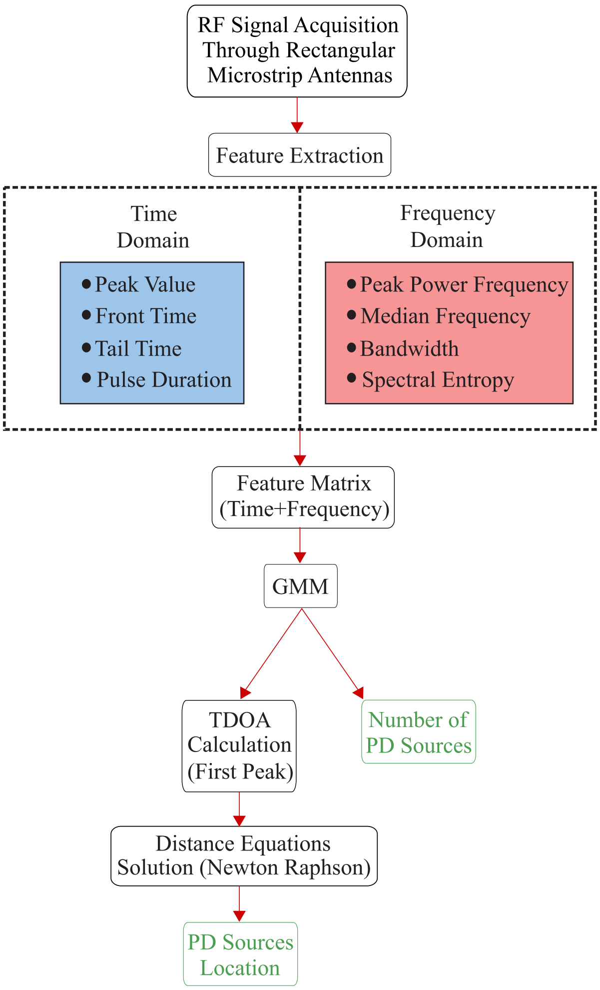

FIGURE 13. **Flowchart of the methodology proposed in [107] for PD location and multiple source separation using GMM.**

proposed model, a maximum location error of only 7.23 cm was obtained for the tests carried out in laboratory, attesting to the efficiency of the method. Furthermore, it was found that the CRP method presents satisfactory location results for signal to noise ratio (SNR) of up to −10 dB, unlike the cross correlation method, which maintains its efficiency only for SNR values up to −3 dB.

In [109], an algorithm that considers the effects of refractions and reflections existing internally to power transformers was proposed. The method presented in [109] uses computer simulations of the electromagnetic waves generated by the PD and obtains the signal propagation time between each point of the transformer 3D space and the UHF sensors positioned in the tank. From the proposed methodology, it is possible to compare the results measured in the field with those computationally calculated so that the position of the PD source can be obtained with the smallest possible location error. For the solution of the TDOA equations, the binary swarm particle algorithm was also used in [109]. The method presented high precision for all simulated cases, resulting in location errors lower than 15 cm. However, the methodology proposed by the authors was not applied in practice.

Still in 2019, a similar study to the one presented in [109] was carried out in [110], in which comparisons were presented between the arrival time instants computationally calculated and those obtained in practice. It is demonstrated that the measured and simulated results were in agreement, attesting that the use of simulations of the wave propagation phenomena inside the transformer represents a powerful tool that can be combined with the development of algorithms for locating defective sources. For the extraction of arrival time instants, both computationally and in practice, the cumulative energy method was used.

In [111], an optimized algorithm was developed for the location of PD sources in power transformers. Three types of non-conventional techniques were evaluated for extracting TDOA from signals obtained by four probe sensors, with an operating range of 150 MHz-1 GHz, inserted in a transformer specially modified for the realization of laboratory experiments. The techniques evaluated were the average time window threshold (ATWT), dynamic cumulative sum (DCS), and the time window contrast function (TWCF). Among the techniques evaluated by the authors, TWCF presented the best location results, with errors lower than 14.5 cm for the three defect positions (tip-flat electrodes) evaluated. To assess the robustness of the developed algorithm, the defect was involved with a cylindrical metallic barrier, resulting in greater location errors. However, the errors remained below 21 cm, which still represent a good location result considering the dimensions of the transformer model used. It is recognized by the authors in their work that the existence of transformers with a sufficient number of oil valves for the application of the proposed methodology is not common. Therefore, it is necessary to study the algorithm developed in conjunction with other types of UHF sensors that can be attached at dielectric windows. In addition, for the effective application of the method, it is necessary to use complementary location techniques, such as the cross correlation. Therefore, the proposed algorithm presents an additional complexity that is not justified by the results obtained, since similar location errors can be achieved through the use of classic techniques (first peak, cumulative energy and cross correlation) as reported in previous works discussed in this section.

In 2020, the impact of noise suppression techniques on the results of locating a database with 300 PD signals measured on a power transformer was evaluated in [112]. For this, two filtering techniques were evaluated: the empirical mode decomposition (EMD) and the WT. For the TDOA extraction, the cumulative energy method is used. After the analyzes, it was found that the use of the WT resulted in smaller errors of location than the EMD, reducing the errors by up to 30 cm. Furthermore, like [98], it is also reported in [112] that the mother wavelet that produced the best filtering and location results was the Daubechies.

In [113] four bio-inspired UHF PMA were used in order to locate a PD source, in laboratory, positioned at four different coordinates within a 200 × 200 × 97 cm^3 dimensional

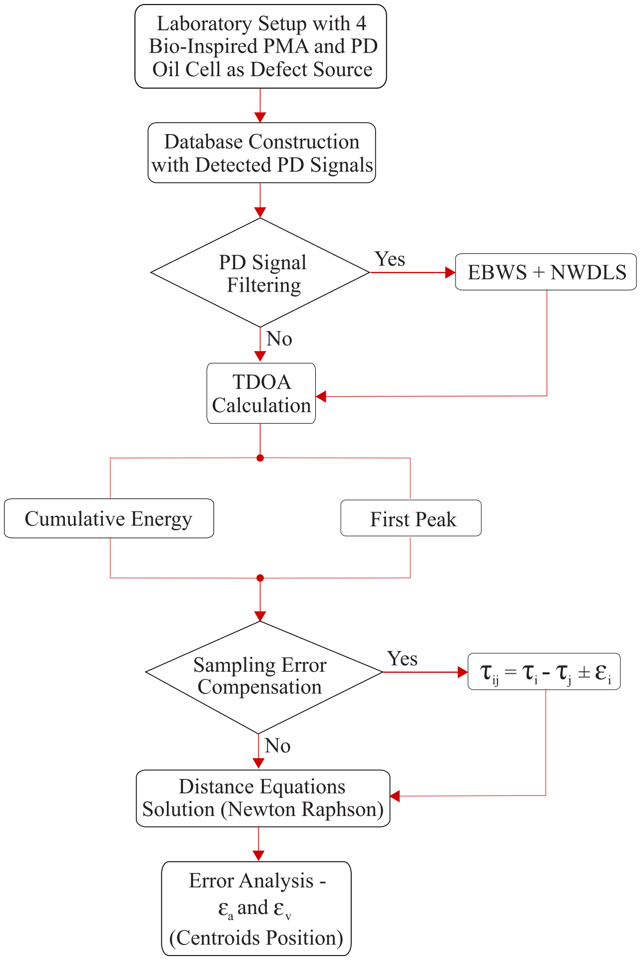

FIGURE 14. General flowchart of the procedures adopted for the study of the location of PD sources developed in [113].

arrangement. For this purpose, the first peak and cumulative energy methods were applied to calculate the TDOA of detected PD signals. In addition, the influence of filtering techniques (based on WT plus energy based wavelet selection–EBWS) and the sampling error of the measuring instrument on the location results was also evaluated in [113]. Better location results for both TDOA calculation methods were obtained through the joint application of filtering techniques and sampling error compensation, resulting absolute errors of only 7.20–9.00 cm for the first peak method, and 5.40–10.96 cm for the cumulative energy method, demonstrating the potential applicability of bio-inspired PMA in the location of PD sources. The general flowchart of the procedures performed in [113] is presented in Fig. 14.

In Table 3, the contributions of the works cited are summarized.

A. TRENDS, CHALLENGES AND OPEN ISSUES

Based on the bibliographic review carried out in the area of defect sources location, it is observed that several publications have successfully addressed the use of the radiometric method from the application of various techniques for TDOA extraction, whether in monitoring of power transformers or high voltage equipment distributed in open area substations. However, only one of the works considered the PMA antennas as a UHF sensor in their experiments or practical applications, in which the vast majority is limited to the use of monopole antennas, capacitive disk sensors and, in only one of the analyzed works, microstrip antennas.

In view of the increasing applicability of bioinspired PMA sensors in the PD detection, presented in Section II, it is necessary to investigate the use of this type of antenna in the location of PD sources. This investigation represents a crucial step for the complete characterization of PMA as a UHF sensor suitable for application in the continuous monitoring of PD, since the radiometric method has as one of the main advantages the possibility of detecting and locating sources of defects. Furthermore, from the investigations, it is possible to determine, according to the gain of the applied PMA, the dimensional limitations of the areas that can be monitored by this type of antenna, checking if the sensors have practical potential for application in the location of defects in power transformers or substations over time.

As can be seen from Table 3, the errors obtained from the TDOA method are relatively small when considering the dimensions of the high voltage equipment under monitoring. However, the TDOA method has some limitations, such as the use of high-acquisition instruments for the correct extraction of the PD signals times of arrival to each of the antennas positioned in the setup applied for the source location, resulting in an expensive method. Thus, the application of the TDOA method in the location of PD radiometric signals is more restricted to equipment whose source coordinates information needs to present significant accuracy, such as power transformers and GIS. Thus, for the general monitoring of open area substations, other techniques that require less complex apparatus, such as the direction of arrival (DOA) [114]–[116] (Fig. 15) and received signal strength indicator (RSSI) [117]–[120] (Fig. 16), can be used to indicate, with relative accuracy, which equipment is defective within the substation, but without further details regarding the position of the internal failure in the equipment.

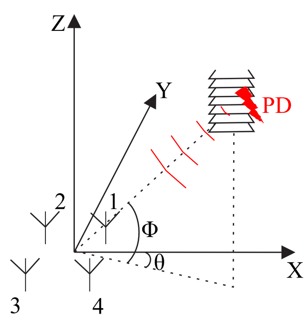

FIGURE 15. Conceptual view of a DOA-based PD location system.

Despite the proposition in [113] of methods for the compensation of measuring instrument sampling errors, it is still necessary to carry out studies that improve the cost-benefit

TABLE 3. Summary of work in the area of PD localization and their respective contributions.

Reference	Contribution	TDOA Calculation method	Location error (cm)
[97]	Applied genetic algorithms to solve the distance equations in location DP sources in transformers.	Cross correlation	16
[98]	Reported that the application of noise filtering techniques results in shifts in signal arrival times, which can lead to significant location errors. Furthermore, they highlighted that the best mother wavelet evaluated in their work was Daubechies.	First peak	18
[99]	Highlighted the relationship between the values of the correlation coefficients and the efficiency of PD location using the cross correlation method.	First peak, cumulative energy and cross correlation	33, 27 and 6, respectively
[100]	Developed a system for the location of defective equipment in substations based on monitoring PD activity.	Cross correlation	–
[70]	Proposed a technique for identifying multiple PD sources by comparing the envelope of the measured UHF signals.	Comparison by envelope	–
[101]	Applied the PSO to solve the distance equations in PD sources location using the radiometric method.	Cumulative energy	12,36
[102]	Studied the efficiency of first peak, cross correlation and cumulative energy techniques in determining TDOA and in the location of defects in power transformers.	First peak, cumulative energy and cross correlation	14,33, 28,84 and 22,11, respectively.
[103]	Proposed the use of statistical models (four-order-cumulant and bispectrum) to determine arrival times.	Statistical models	24
[104]	Performed defect location tests with a real transformer in laboratory, allowing the comparison between the real position of the defect and the estimated one from the transformer model.	–	10
[105]	Proposed a method for verifying the optimal position of sensors in transformers, so that the location error is minimal.	–	30,7
[106]	Evaluated the applicability of the radiometric method in conjunction with the TDOA for defects location in transformer bushings using an array of four spiral antennas in a T shape.	–	20
[107]	Applied microstrip antennas, instead of monopole antennas, for separation of multiple sources and defects location in substations over time.	GMM plus first peak	1,4% (Result given only in percentage)
[108]	Proposed a new model, called CRP, to help estimate arrival times in power transformers filled with vegetable oil.	CRP	7,23
[109]	Defined a location algorithm that considers the effects of refractions and reflections existing internally to power transformers based on simulations of their geometric model.	–	15
[110]	Presented comparisons between the arrival times obtained in practice and those calculated computationally from simulations considering internal reflections and refractions of the power transformers.	Cumulative energy	–
[111]	Developed an optimized algorithm for PD location in transformers using probe-type UHF sensors.	TWCF	14,5
[112]	Evaluated the impact of two filtering techniques, EMD and WT, on the results of PD location signals in a power transformer.	Cumulative energy	–
[113]	Evaluated the application of bioinspired PMA in PD location sources using conventional TDOA techniques.	First peak and cumulative energy	9,00 and 10,96, respectively.

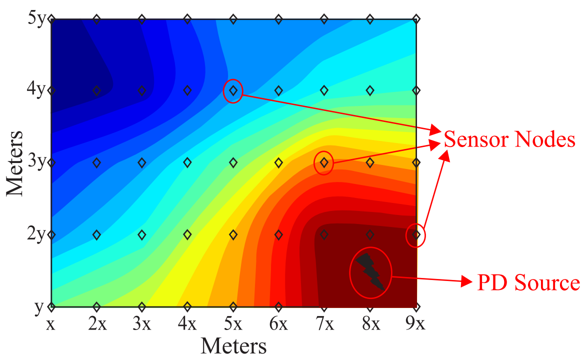

FIGURE 16. Conceptual view of a RSSI (fingerprint map) based PD location system.

ratio of the TDOA method, i. e., that result in the use of simpler acquisition equipment and still provide good location accuracy. Furthermore, as discussed in this paper, in practical applications, PD radiometric signals are subject to reflection, refraction, diffraction and attenuation phenomena that can cause errors in the TDOA calculation, especially in the presence of obstacles, as illustrated in Fig. 17. Thus, further studies are required for the proper compensation of these phenomena in location algorithms, which can be made from the creation of digital twins of the monitored high-voltage equipment. From the computational models, it will be possible to accurately identify the practical time delays due to these propagation phenomena, resulting in location estimations even more accurate. From a more accurate information regarding the 3D position of the defect, it is possible for the maintenance teams to act more efficiently and quickly, contributing significantly to the time reduction and cost necessary for the equipment repair. From the accurate source location, it is also possible to verify the severity of the discharge, since more intense discharges in certain locations of the equipment's insulating system can be more damaging than those located in other areas.

Finally, the application of the auxiliary calibration curves described in Section II-A can be improved through the use of high-precision location algorithms, since signal attenuation

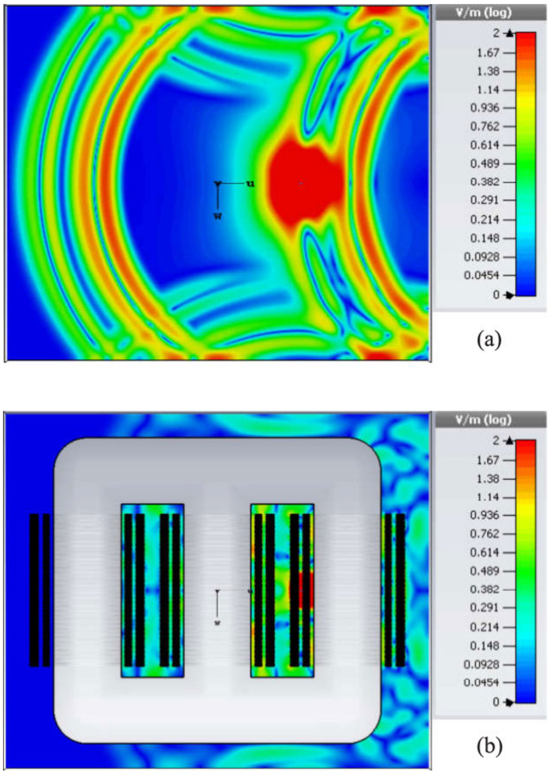

FIGURE 17. PD wave propagation in a power transformer tank: (a) without obstacles; (b) with obstacles.

compensations can only be carried out effectively from an estimate of the actual position of the PD source. In addition, the accurate location of the PD source can also be very useful for the application of time series and other lifetime predicting algorithms for high voltage equipment.

Therefore, the trends, challenges and open issues related to studies in location of PD sources in high voltage equipment can be summarized as follows:

- Location studies using PMA sensors (bio-inspired or not);
- Development of TDOA based location algorithms with lower cost and high efficiency;
- Proper compensation of propagation phenomena in TDOA algorithms based in computational models;
- TDOA location algorithms as an auxiliary tool for the development of UHF calibration procedures.

VI. CONCLUSION

In this paper, it was presented a comprehensive survey on the area of detection, classification and location of partial discharge (PD) sources using the radiometric method. First, it was presented the evolution of the ultra high frequency (UHF) method in the aforementioned areas in high voltage equipment, mainly gas insulation substations (GIS) and power transformers. Then, it was provided detailed reviews, analyses, comparisons and the main contributions regarding development and optimization of UHF sensors for applications in the PD detection, classification and PD location sources. In addition, it was outlined important challenges, open issues, as well as future research directions related to the thematic. In this survey is provided a quick and comprehensive understanding of the current state of the arts in detection, classification and location of PD sources in high voltage equipment's, attracting more researchers into this area.

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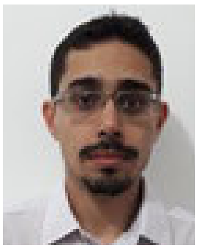

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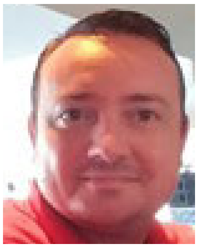

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