A new technique for separation of partial discharge sources and electromagnetic noise in radiofrequency measurements using energy ratios of different antennas

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Abstract
One of the main tools for monitoring the condition of high voltage equipment is the measurement of partial discharges (PD). The electromagnetic (EM) radiation originated from this degradation phenomenon can be captured by various types of ultra-high frequency (UHF) antennas carefully designed and optimised for specific frequency bands. However, the presence of environmental noise may limit the use of this technique. Different types of monopole antennas normally used in UHF PD measurement have been evaluated in order to validate the performance of a novel separation technique of EM sources. Accordingly, a new separation technique based on the energy ratio of the captured signals was developed, considering noise interferences. The results revealed that the new technique allows an adequate separation, even when three sources act simultaneously.

1 | INTRODUCTION

The measurement of electromagnetic (EM) radiation emitted by partial discharges (PD) is currently one of the most widely used methods to monitor the condition of different electrical assets such as gas-insulated systems (GIS), cables, transformers and rotating machines, among others [1–3]. Normally, the measurement process is carried out through ultra-high frequency (UHF) antennas capable of capturing relevant information in broadband of frequencies ranging from tens of megahertz to gigahertz without the need of galvanic contact with the equipment under test [4, 5]. However, the presence of environmental noise or series of pulses coming from simultaneously acting external EM emission sources or multiple PD sources can generate unwanted interferences, making the diagnosis, identification or location of sources difficult in some cases, thus being necessary the previous application of a separation process to each of the signals that have been captured [6–8].

Most of the works in literature have mainly focused on the separation of sources for the very high frequency (VHF) range from inductive and/or capacitive sensors [9–11]. Due to the complex spectral and temporal characteristics of the signals captured by the antennas, the application of these VHF techniques cannot be considered a good alternative when it comes to performing a correct separation in UHF measurements [7]. The few techniques that have focused directly on using antennas for sources separation have some limitations when the spectral components of the PD are incipient compared to the components associated with external noise, which is very common in industrial environments [1, 5]. Furthermore, the separation capability of these techniques may not be very efficient in some cases because they use only the radiation captured with a single antenna. For this reason, the performance of the technique will ultimately depend on the frequency that the antenna is optimised for and the frequency range emitted by the PD.

With the recent development of new UHF antennas with higher bandwidths, these techniques could have better results during the separation processes because a higher spectral content of the signal could be used [2, 3].

On the other hand, several UHF-based methodologies such as the Wavelet analysis and the Total Variation Theory [7]...
have been successfully proved as noise compensation techniques for PD detection. However, the separation of multiple sources of PD is crucial for systems maintenance because each PD type can contribute to the degradation of an insulation system in different ways. In this short paper, a novel instrumentation technique for separating PD sources and EM noise is presented, considering the noise interference on the measurement system. The information captured simultaneously by an array of two monopole antennas allows two energy relationships to be established for the same PD or external noise source, both represented as a point on a two-dimensional separation map. The experimental results obtained on different test objects confirm that this promising separation technique is capable of adequately separating multiple sources, even when they act simultaneously.

2 | EXPERIMENTAL SETUP

The circuit and the instrumentation used in the PD measurement and generation process correspond to the indirect circuit detailed in IEC-60,270 standard [6, 8]. Three monopole antennas were used in different arrangements to capture EM emissions from PD sources and EM noise. According to their dimensions, the length of the antenna defines its resonance frequencies, that is, the frequency at which the antenna is optimised. In this case, the 5-cm monopole is optimised to 1.5 GHz, the 10-cm monopole to 0.75 GHz and the 15-cm monopole to 0.5 GHz. More information about these antennas and the measurement circuit used can be found in References [5, 7, 8, 10]. As observed in Figure 1, the signal acquisition in the test objects was carried out through two different antennas (A1 and A2). A1 corresponds to the closest antenna to the PD emission source and A2 to the furthest antenna. A1 and A2 were connected to a PXI high-speed acquisition system, with a 12.5 GS/s sampling rate, 8 bits of vertical resolution and 3 GHz of bandwidth. Since the first antenna adaptation frequencies are ≤1.5 GHz, the acquisition system was configured at a sampling frequency of 4 GS/s, and each signal was stored with a window width of 1 μs. Additionally, a commercial PD measurement system was used to validate the presence of PD phenomena. For the experimental results detailed in Section 4, three different test setups were implemented:

2.1 | NOMEX paper stacked

This test object is made up of three sheets of NOMEX paper stacked and vacuum sealed. The central sheet was perforated with a 1 mm diameter needle, aiming to create a cylindrical vacuole to generate internal PD. These sheets were placed between two electrodes and subjected to high voltage. With this test object, a stable PD activity was obtained at 4.5 kV. This type of material is usually employed in high voltage machines due to their high thermal and mechanical resistance.

F I G U R E 1   Experimental setup

2.2 | Methacrylate discs

Three perfectly fused methacrylate discs without air gaps were used for this test object. Like the previous test object, the central disc was drilled to obtain a cylindrical vacuole (3 mm in height). Subsequently, two electrodes applied a voltage level of 22 kV, achieving stable internal PD activity.

2.3 | A contaminated ceramic bushing

This is a bushing insulator superficially contaminated with saline, simulating a very common condition in coastal environments, thus achieving a stable surface PD activity at a low voltage level. Additionally, the test object was intervened to generate a simultaneous additional source of internal PD. Both PD sources were stable at a voltage level of 15 kV.

To guarantee that both antennas simultaneously captured the EM emission from a PD or noise source, the authors configured the acquisition system on synchronous mode. The measurement process in each test object started at a low trigger level and a low voltage level (800 V), and thus, only EM emissions from external noise sources within the laboratory were captured with both antennas. The group of noise signals captured with A1 and A2 were called $EM_{41}$ and $EM_{42}$ respectively. After that, the trigger level was adjusted above the noise level, and the voltage was raised to a stable PD level, ensuring PD emissions. For this configuration, signals captured
by $A_1$ and $A_2$ were called $PD_{A_1}$ and $PD_{A_2}$, respectively. Finally, the voltage level of the previous configuration was kept, and the trigger was adjusted to a low level. Therefore, simultaneous sources of PD and EM noise were captured. These mixed signals captured by $A_1$ and $A_2$ were represented, respectively, by the parameters $MS_{A_1}$ and $MS_{A_2}$. The number of signals stored by each antenna was 200 pulses when only a single source was present. For two or more sources, the number of pulses was 700.

3 | NEW DATA SEPARATION TECHNIQUE

During any UHF measurement process, the EM noise that has been captured by an antenna can be classified into several categories [5, 7, 8]:

- Stochastic noise, random in both time and amplitude, such as corona or plasma in air that can emit energy up to 500 MHz.
- Periodic-pulsing noise from thyristor operation, that is, inverters and voltage or current regulated sources, among others.
- Continuous sinusoidal noise from communication systems such as FM radio, digital TV, aeronautical radio navigation, digital audio broadcasting, global system for mobile communications and Wi-Fi.

For this reason, in order to carry out a correct separation process, it is necessary that the implemented technique can effectively differentiate the EM emissions that come from PD sources from those associated with external sources of stochastic or periodic-pulsating noise. Likewise, it is required that the performance of the technique itself is not affected by the influence of continuous sinusoidal noise, because when the spectral content of this type of noise is very high, the separation of the sources can be much more complex [6].

According to the above, the proposed separation technique begins by calculating the average Fast Fourier Transform (FFT) of the environmental noise captured by $A_1$ and $A_2$ ($S_{over1}(f)$ and $S_{over2}(f)$). It is important to note that, in order to correctly measure the EM noise, the sensors must not be too close to the possible PD source. After that, considering these two data groups as $EMN_{A_1}$ and $EMN_{A_2}$, two filtering thresholds to $S_{over1}(f)$ and $S_{over2}(f)$, are calculated taking 7% of the maximum peak of the spectral power, according to Figure 2. This procedure allows selecting, for each antenna, the frequency bands ($f$) where the average spectral power of the noise is below the established threshold, since the remaining bands (in black) constantly have a strong influence of continuous sinusoidal noise. Experimentally, other threshold values between 1% and 15% were analysed. However, for the magnitude and type of noise captured in the laboratory tests, the best results in terms of separation were obtained with 7%. The authors recommend that the filtering threshold be between 3% and 10% for each of the antennas.

$$ER_{A1} = \frac{\sum_{f}^{f^*} |S_{A1}(f) - S_{over1}(f)|^2}{\sum_{f}^{f^*} (|S_{A1}(f)|^2 + |S_{A2}(f)|^2)}$$

$$ER_{A2} = \frac{\sum_{f}^{f^*} |S_{A2}(f) - S_{over2}(f)|^2}{\sum_{f}^{f^*} (|S_{A1}(f)|^2 + |S_{A2}(f)|^2)}$$

where $S_{A1}(f)$ and $S_{A2}(f)$ are the magnitudes of the FFT of the measured signals, $i$ corresponds to the different frequency bands selected and runs through each of these bands increasingly, $f^*$ is the maximum band of the selected frequencies, and $f_i$ is the maximum frequency band of the original signals and will depend on the sampling frequency and the bandwidth of the acquisition system.

4 | RESULTS AND DISCUSSION

For the experimental results detailed in this section, three different antenna arrays were used. Array one includes antennas $A_1$ and $A_2$ separated at the same distance from the test
object; array two includes \( A_1 \) as the antenna optimised for higher frequency bands (closest to the test object) and \( A_2 \) as the antenna adapted for lower frequencies (farthest from the test object). Finally, in array 3, the position of the antennas of the previous arrangement is inverted, taking the optimised antenna at lower frequencies as \( A_1 \), and \( A_2 \) as the antenna with the highest optimisation frequency. Applying the measurement procedure described in Section 2, for each array we obtain: \( EMN_{A1}, EMN_{A2}, PD_{A1}, PD_{A2}, MS_{A1} \) and \( MS_{A2} \). Then, in order to validate the type of source corresponding to the clusters obtained from the signals of \( MS_{A1} \) and \( MS_{A2} \), a comparison has to be made between the FFT of the signals associated with each cluster, and the average FFT of \( EMN_{A1}, EMN_{A2} \) or \( PD_{A1} \) and \( PD_{A2} \). This way, it is possible to establish whether the obtained cluster belongs to a PD source or to a noise source.

**Experiment 1** In this experiment, the sheets of NOMEX paper described in Section 2 were used as test object. According to the results obtained, for arrangement 1 and 2 using the 5 cm monopole antenna and the 10 cm monopole antenna, it was not possible to identify in \( MS_{A1} \) and \( MS_{A2} \) the presence of the two types of sources. As seen in the separation map in Figure 3a, only a single cluster formed by the signals from both types of sources is evident. However, using array 3, where the 10 cm monopole antenna is closest to the test object, it was possible to visualise and verify the presence of two different clusters, one associated with PD (shaded in green) and another associated with EM noise (shaded in red), see Figure 3b. During the measurement process, the spacing of the antennas to the test object was adjusted to 13.2 cm for \( A_1 \) and 23.5 cm for \( A_2 \).

**Experiment 2** For the generation of PD in this experiment, the methacrylate disc with internal vacuole described in Section 2 was used as the test object. During this measurement process, the same antennas and distances from the previous experiment were kept for the three arrays. Again, with arrays 1 and 2, it was not possible to obtain adequate clusters separation on the separation map during simultaneous source acquisition. As in the previous experiment, only with array 3 it was possible to show the presence of two different clusters, see Figure 3c. According to the spectral content of the signals associated with each cluster, it was confirmed that the red shaded cluster corresponds to EM noise sources, and the green shaded cluster corresponds to PD sources on the methacrylate disk. Since for the above measurements, source separation was possible only when the antenna optimised at lower frequency bands was located closer to the PD emission source, a change was made in order to evaluate if such behavior was the same with a different type of antenna. In this case, the 10 cm monopole antenna was replaced by a 15 cm monopole optimised at 0.5 GHz and the separation distances were kept the same as in the previous measurement for both antennas. For this measurement process on the methacrylate disc, it was observed that, once again, with arrays 1 and 2 it was not possible to establish a source separation. Only when using arrangement 3 was possible to identify the presence of two different clusters on the separation map. When evaluating the signals associated with each cluster (see Figure 3d), it is evident that the cluster associated with EM noise (shaded in red) tends to be located again to the left of the cluster associated with PD in the test object. This behavior is similar to that obtained in the previous separation processes, which confirms that \( ER_{A1} \) and \( ER_{A2} \) is slightly more relevant for emissions from PD sources.

Finally, two new measurement processes were performed on this same test object, using the 10 and 15 cm monopole antennas. For the first measurement process, and using the three antenna arrays, the separation between \( A_1 \) and the test object was adjusted to 20 cm, and for \( A_2 \), the separation was 26 cm. The second measurement process was performed with a completely different distance between the antennas and the test object (\( A_1 \) at 15 cm and \( A_2 \) at 30 cm). According to the results obtained in both measurement processes, it is confirmed that it is only possible to obtain an adequate separation between the PD and noise sources when \( A_1 \) corresponds to the antenna that is optimised at the lowest frequency, and there is a greater separation between \( A_2 \) and the test object. The separation maps obtained with both measurement processes are shown in Figures 3e and 3f.

**Experiment 3** For this last experiment, a contaminated ceramic insulator was used, which was adjusted to generate stable activity of surface and internal PD at the same voltage level. During the measurement process, the 10 and 15 cm monopole antennas were used to establish the three antenna arrays. Also, antenna \( A_1 \) was located 15 cm away from the test object, while antenna \( A_2 \) was located at a distance of 30 cm. As seen in Figure 3g, the presence of three different clusters is evident when array 3 is used. According to the figure, it was confirmed that the red shaded cluster corresponds to the noise sources, the green shaded cluster corresponds to internal PD sources, and the blue shaded cluster corresponds to surface PD sources. As in all previous cases, with arrays 1 and 2 it was not possible to separate these three types of sources. Similar to the results obtained in the measurement processes of the previous experiments, the noise cluster was located on the main diagonal of the separation map.

According to the results obtained in these three experiments, the separation process was satisfactory only when the antennas were positioned according to array 3, where the antenna optimised for the lowest frequency is closest to the test object. Maintaining this arrangement, the separation capability of the technique was satisfactory even when more than two PD sources acted simultaneously over the test object, as in the case of experiment 3.
5 | CONCLUSIONS

In this short paper, we propose a new UHF technique for the separation of PD sources and EM noise based on the energy ratios obtained for two antennas optimised at different frequency bands. During the measurement process, different types of monopole antennas deployed in three different arrangements were used, this procedure allowed evaluating the performance of the technique based on the position of the antennas. The results obtained in each measurement process, conclusively indicated that, to obtain an adequate separation of the PD and noise sources, it is necessary that the two antennas are positioned at different distances from the asset under test and that the antenna adapted to measure at a lower frequency be located at a shorter distance. When the position of the antennas was reversed or they were at the same distance from the emission source, it was not possible to separate the sources.

On the other hand, it was observed that the adjustment of the threshold for the selection of the frequency bands required for the calculation of ER_{A1} and ER_{A2} should be kept between 3% and 10% depending on the behavior of the noise. A very low or very high value in the threshold will directly affect the source differentiation causing a cluster’s overlap in the separation map. Likewise, when evaluating the clusters associated with EM noise in the different separation maps, it is observed that the values of ER_{A1} and ER_{A2} are lower than those obtained for the clusters associated with PD. This concurs with the structure of the proposed technique, which disregards spectral power in the frequency bands with the greatest influence of external noise.

Finally, it should be noted that, for this technique to deliver good results in a real measurement process, it is necessary for the system to carry out a first measurement of EM noise with both antennas in the environment where the monitoring is to be carried out, not too close to the possible PD source. Subsequently, the measurement system must be deployed in the vicinity of the asset to be monitored, and a new acquisition is made, storing the EM emissions from simultaneous sources of PD and EM noise.

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REFERENCES

1. Hu, Y., et al.: Design of a distributed UHF sensor array system for PD detection and location in substation. IEEE Trans. Instr. Meas. 68(6), 1844–1851 (2019)
2. Qi, Y., et al.: Design of ultra-wide band metal-mountable antenna for UHF partial discharge detection. IEEE Access. 7, 60163–60170 (2019)
3. Rodrigo Mor, A., Castro Heredia, L.C., Muñoz, F.A.: A magnetic loop antenna for partial discharge measurements on GIS. Int. J. Elect. Power Energ. Systems, 115, 105514 (2020)
4. Ishak, M., et al.: Design and optimization of UHF partial discharge sensors using FDTD modeling. IEEE Sensors J. 17(1), 127–133 (2017)

5. Albarracín, R., Ardila-Rey, J.A., Mas'ud, A.A.: On the use of monopole antennas for determining the effect of the enclosure of a power transformer tank in partial discharges electromagnetic propagation. Sensors. 16, 148 (2016)

6. Albarracin, R., et al.: Separation of sources in radiofrequency measurements of partial discharges using time–power ratio maps. ISA Trans. 58, 389–397 (2015)

7. Tang, J., Zhou, S., Pan, C.: A denoising algorithm for partial discharge measurement based on the combination of wavelet threshold and total Variation theory. IEEE Trans. Instrum. Meas. 69(6), 3428–3441 (2020)

8. Robles, G., et al.: Antenna parametrization for the detection of partial discharges. IEEE Trans. Instrum. Meas. 62(5), 932–941 (2013)

9. Rodrigo Mor, A., Castro Heredia, L.C., Muñoz, F.A.: Effect of acquisition parameters on equivalent time and equivalent bandwidth algorithms for partial discharge clustering. Int. J. Elect. Power Energy Systems. 88, 141–149 (2017)

10. Ardila-Rey, J.A., Montero, E., Medina Poblete, N.: Application of meta-heuristic approaches in the spectral power clustering technique (SPCT) to improve the separation of partial discharge and electrical noise sources. IEEE Access. 7, 110580–110593 (2019)

11. Ardila-Rey, J.A., et al.: A comparison of inductive sensors in the characterization of partial discharges and electrical noise using the chromatic technique. Sensors. 18(4), 1021 (2018)

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