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# Partial Discharge Localization Using Electromagnetic Time Reversal: A Performance Analysis

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**ABSTRACT** In this study, first, a comparison on the application of electromagnetic time reversal (EMTR) and time difference of arrival (TDoA) in partial discharge localization in power transformers is presented. A two-dimensional finite-difference time-domain simulation is used to calculate the signal recorded by the sensors. Results show that, in a transformer tank excluding its windings, both methods yield similar results in terms of location accuracy, although the EMTR method only needs one sensor to localize the partial discharge (PD) source while the TDoA method needs at least three sensors in the 2D localization problem. However, the presence of transformer windings leads to a degradation of the performance of the TDoA method if the line of sight from the source to the sensor is blocked by any of the winding blocks. On the other hand, the presence of the transformer windings has an effect on the localization of PD sources that occur between two adjacent phase windings when the distance between the outer winding distances is shorter than the minimum wavelength, $\lambda_{\min}$. The degradation is directly caused by the diffraction limit. It is shown that, if the distance between two adjacent phase windings is greater than $\lambda_{\min}$, the EMTR process can locate PD sources occurring between two adjacent phase windings with acceptable accuracy. A case of occurrence of PDs in close proximity (less than $\lambda_{\min}/2$) to a single metallic object is analyzed both numerically and experimentally. The analysis reveals that although a degradation in the accuracy of the localization is observed compared to the case of longer distances between the PD source and the metallic object, a reasonable localization error of 10 mm (corresponding to $\lambda_{\min}/10$) is obtained.

**INDEX TERMS** Experimental analysis, partial discharge localization, time difference of arrival, electromagnetic time reversal process, transformer tank.

## I. INTRODUCTION

Power transformers are one of the key components of power systems. Partial discharges (PDs), which are due to abnormal local enhancements in the electric field within the transformer tank are the main cause of damage to the insulation system of power transformers. Measurement methods based on electrical, chemical, acoustic and electromagnetic techniques have been deployed to study this phenomenon in power transformers [1]–[7]. Electromagnetic based techniques have received more attention recently due to their robustness against external noise and their ability to detect weak PDs.

PDs produce electromagnetic waves in the range of 300 MHz up to 3 GHz [8], [9]. As a result, electromagnetic source detection methods are applied to locate PDs in the ultra-high-frequency (UHF) band. Electromagnetic methods use generally the time difference of arrival (TDoA) to localize PDs [10], [11]. In a three-dimensional problem, this method

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needs at least four synchronized sensors to provide source localization. Even with four sensors, an accurate location of the PD source cannot be achieved in the presence of transformer windings since the line of sight assumption of the TDoA method is no longer guaranteed. The effect of the presence of the transformer windings on the arrival time of the signal is investigated in [12]. In this regard, the effect of the sensor positioning on the amplitude of the recorded signal is discussed by Du *et al.* [13]. Simulations in the presence of transformer windings have been validated against measurements in [14].

In order to improve the performance of TDOA-based PD location methods, a new algorithm using the binary swarm optimization technique was used in [15] and tested on a relatively complex model of a transformer tank which includes reflection, refraction and diffraction of the electromagnetic waves taking into account the transformer's equipment, including the walls of the transformer tank. The proposed algorithm was able to locate the PD source with location accuracies of about 15 cm [15].

More recently, the electromagnetic time reversal (EMTR) technique was proposed to locate PD sources in power transformers[16], demonstrating the ability of the method for source localization in complex and heterogeneous media [17], [18]. The metallic enclosure that forms the transformer tank is a cavity. The power transformer windings make the interior of the tank a rich scattering environment for the time reversal localization process, whose performance has been shown to improve in the presence of scatterers [19]. The focusing property of electromagnetic time reversal cavities has been proven both experimentally and theoretically [20]–[22]. Recently, the application of electromagnetic time reversal cavities has been exploited to locate EMI sources [23], [24]. It has been shown that using a single sensor within a cavity is equivalent to the use of an infinite number of sensors in free space.

In this paper, first, the time reversal method and the TDoA method in terms of their performance for PD source localization in power transformers are compared. The efficiency of both methods for various source locations and geometries is studied. Furthermore, the EMTR performance to localize PD sources using only one sensor is investigated. Also, case studies are investigated in which the EMTR's ability to localize the PD accurately breaks down when electrical distances between two adjacent phase windings fall below a threshold equal to the PD minimum radiated wavelength.

This paper is organized as follows. Section II briefly summarizes the EMTR and TDoA methodologies to locate PD sources, as well as the considered 2D model for the transformer used in this study. Section III presents a comparison between the EMTR and the TDoA techniques. Section IV presents different case studies in which the performance of the single-sensor EMTR technique to locate PD sources is evaluated. Section V presents experimental data aimed at analyzing the performance of the EMTR technique in locating PDs occurring near a metallic surface. Finally, concluding remarks are given in Section VI.

## II. METHODOLOGY AND SIMULATION SCHEME

### A. TIME DIFFERENCE OF ARRIVAL

The principle of PD source localization using TDoA includes obtaining electromagnetic fields by at least three separated sensors in a 2D problem. The differences in the times of arrival of the signals at the sensor locations are used to form a system of nonlinear equations given in (1) [12].

$$\sqrt{(x-x_i)^2+(y-y_i)^2}+\sqrt{(x-x_j)^2+(y-y_j)^2}=\Delta t \quad (1)$$

in which $\Delta t$ is the difference in arrival of the signal to two sensors $i$ and $j$ with coordinates $(x_{\mathrm{i}}, y_{\mathrm{i}})$ and $(x_{\mathrm{j}}, y_{\mathrm{j}})$.

By solving the resulting set of equations, the location of the PD source can be obtained. Various algorithms have been applied to improve the TDoA-based PD source localization (e.g. [14]).

### B. ELECTROMAGNETIC TIME REVERSAL

Maxwell's equations in lossless media are known to be invariant under the time reversal operator [25]. As a result of the time reversal invariance, the waves from the source that originally diverged from it, can be made to converge back to it, as if time were running backwards. As explained in the three steps to be presented below, electromagnetic field signals measured at a distance from the source need only be time-reversed and back-injected into the original medium to produced waves that propagate back and eventually concentrate at the source location, creating a diffraction limited focal spot [26]. To apply the time reversal process to the PD source localization problem, one needs to follow the following three steps[16]:

(i) The electromagnetic waves from the PD source are measured at one or multiple locations (forward-time). This step, called the forward-time step, can be done either numerically or experimentally.

(ii) The recorded waveforms are time-reversed and back-injected into the solution space in a simulation environment (backward-time step).

(iii) A criterion to locate focal points created by constructive interference is used to determine the position of the original PD source. To identify the focal spot of the back-injected waves, several criteria can be used (e.g., maximum field, minimum entropy, cross correlation [24], [27], [28]). Further discussion on the maximum field criterion can be found in [24]. In this paper, the maximum electric field power intensity criterion is used.

### C. CONSIDERED 2D TRANSFORMER MODEL

Figure 1 shows the overall geometry of a transformer tank that will be used in the analysis. The size of the tank is $1000\times 500$ mm$^2$. The walls of the transformer tank are considered to be metallic, perfect electric conductors (PEC). Three metallic

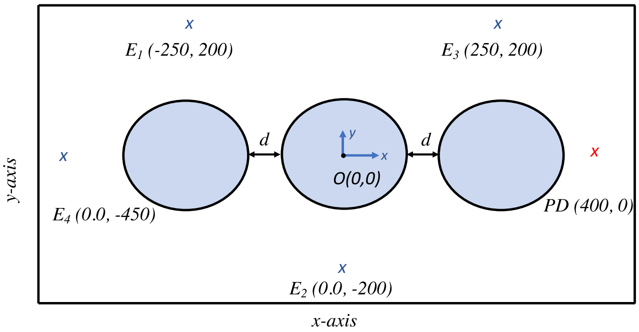



**FIGURE 1.** **Two-dimensional geometry of the transformer tank including the windings. All the values are in millimeters. $E_1$, $E_2$, $E_3$, and E4 correspond to the locations of the sensors. PD corresponds to the location of the partial discharge (red cross).**

circles with a 100 mm radius are used to represent the solid-shell cylindrical windings of the transformer. Apart from the three considered windings, the transformer tank is considered to be empty. Four sensor locations provided in Table 1 are used in this study. The subset used for each case study is given in its associated description. Four points, denoted $E_1$, $E_2$, $E_3$ and $E_4$ show the locations of the sensors. The location of the partial discharge source will be identified as PD in the figures. One such partial discharge source is shown in Figure 1 (red cross). An infinitesimal dipole source is considered as a PD source. The dipole source is excited with a 3-GHz bandwidth Gaussian pulse.

**TABLE 1.** **Considered locations of the sensors.**

| Sensor | Location (m) |
|---|---|
| $E_1$ | (-250, 200) |
| $E_2$ | (0, -200) |
| $E_3$ | (250, 200) |
| $E_4$ | (-450, 0) |

## III. COMPARISON BETWEEN EMTR AND TDOA

A two-dimensional finite-difference time-domain (FDTD) numerical code will be used to calculate the electric field within the transformer tank in the forward and backward time steps. Considering the axis of symmetry of a two-dimensional transformer tank, the numerical code solves the transverse magnetic modes ($TM_z$) of Maxwell's equation given in (2),

$$\begin{cases} \dfrac{\partial E_z}{\partial t} = \dfrac{1}{\varepsilon}\left(\dfrac{\partial H_y}{\partial x} - \dfrac{\partial H_x}{\partial y} - \sigma E_z - J\right) \\ \dfrac{\partial H_x}{\partial t} = \dfrac{1}{\mu}\left(-\dfrac{\partial E_z}{\partial y} - \sigma H_x\right) \\ \dfrac{\partial H_y}{\partial t} = \dfrac{1}{\mu}\left(\dfrac{\partial E_z}{\partial x} - \sigma H_y\right) \end{cases} \tag{2}$$

in which $\varepsilon$, $\mu$ and $\sigma$ are, respectively, the permittivity, permeability and conductivity of the medium.

Identical scenarios will be considered to investigate the performance of the time reversal and TDoA techniques. The computational domain is meshed using an equally-spaced square mesh with a cell length of 2.5 mm. In the presented simulations, the time step and number of time steps are 5.3 ps and 4000, respectively.

### A. CASE STUDY ONE: TRANSFORMER WITHOUT WINDING

Here, the simplest case study is assumed, in which an empty tank is considered as a transformer. The location of the used sensors and the PD source are given in Figure 1. Figure 2 provides the comparative analysis of the obtained results using both, the EMTR and the TDoA techniques.

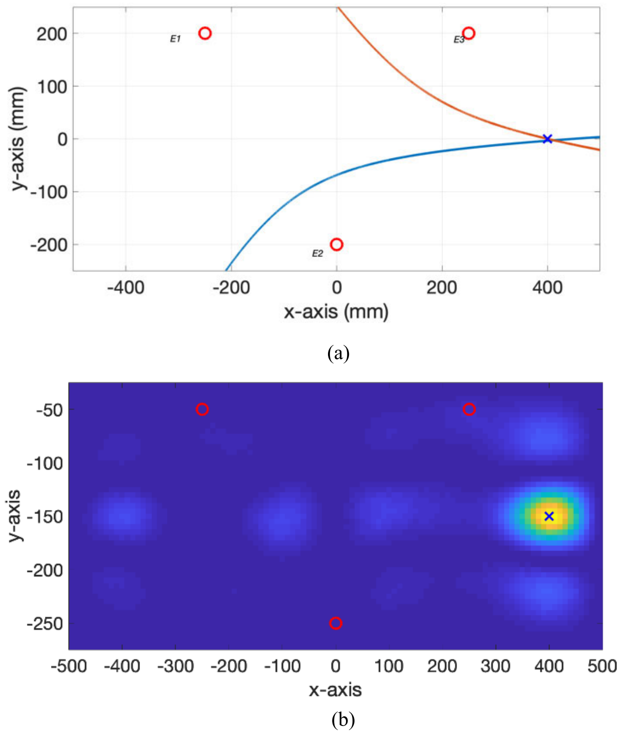



**FIGURE 2.** **PD source localization in a Transformer model without winding. a) TDOA: hyperbolic branches corresponding to the propagation times from the PD to the sensors E2 and E3. The hyperbolic branch defined by the time difference of arrival between sensors 2 and 3 is presented in red. The hyperbolic branch defined by the time difference of arrival between sensors 1 and 2 is represented in blue. b) TR: Normalized distribution of the maximum electric field power intensity at each location over all time steps. Red circles show the locations of the sensors and the blue cross shows the estimated location of the PD source.**

The results presented for the TDoA method can be understood as follows. For line-of-sight conditions, the time difference of arrival of the radiation of the PD source to two spatially separated sensors is proportional to the difference between the distances. The time difference of arrival can therefore be used to draw a hyperbolic branch that is the set of possible source locations.

Two pairs of sensors define two different hyperbolic branches whose intersection is the location of the source. The blue and red lines in Figures 2a and 3a are the hyperbolic branches for two different pairs of sensors. Only the hyperbolic branches that correspond to a shorter propagation time from the PD source to sensors $E_2$ and $E_3$ are shown in Figure 2a (TDoA). Figure 2b shows the normalized distribution of the maximum electric field power intensity at each location over all time steps used for the EMTR method. The EMTR location error is less than a mesh cell, while the TDoA location error is 11 mm. It should be noted that an electric field threshold of $10^{-9}$(V/m) is used to determine the onset time of each signal in the TDoA method. Once the onset times are obtained, their time difference is used to draw the two hyperbolas. The intersection of the two hyperbolas yields the estimated location of the PD source.

### B. CASE STUDY TWO: TRANSFORMER WITH WINDINGS

In this case study, the windings of the transformer are included as presented in Figure 1. Figure 3 provides the result of the PD source localization for both the TDoA and the EMTR methods. Only the hyperbolic branches that correspond to a shorter propagation time from the PD source to sensors $E_2$ and $E_3$ are shown in Figure 3a. It can be observed that the TDoA method estimates the location of the source (the point where the hyperbolas cross) to be outside of the tank, which is shown as a dashed line rectangle in the figure. The localization error is about 489 mm. On the other hand, the EMTR method (Figure 3b) can still provide accurate results, similar to the first case study. A discussion here is in order on the reason for the failure of the TDoA in this case. As can be seen in Figure 1, there is no line-of-sight view from the PD source to the sensors $E_1$ and $E_2$. From the hyperbolic branches drawn in Fig. 3a, it can be inferred that the first arriving wave is coming from the second hop reflection from the right wall of the cavity. Since the arrival time of the wave does not correspond to that of the direct wave, the TDoA method does not work properly. Further discussion on the performance of the TDoA technique for the localization of PD sources is provided in the supplementary material.

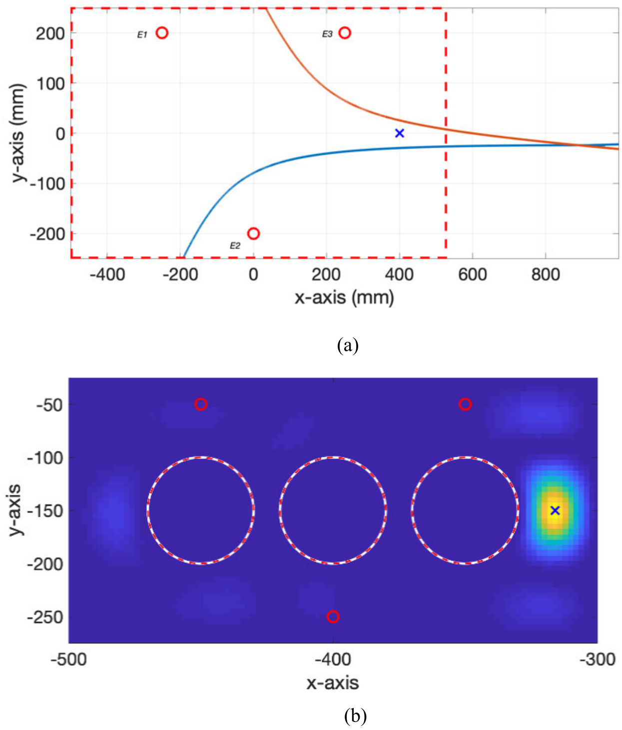



**FIGURE 3.** PD source localization in a Transformer with windings. a) TDOA: hyperbolic branches corresponding to the propagation times from the PD to the sensors E2 and E3. The hyperbolic branch defined by the time difference of arrival between sensors 2 and 3 is represented in red. The hyperbolic branch defined by the time difference of arrival between sensors 1 and 2 is represented in blue. b) EMTR: Normalized distribution of the maximum electric field power intensity at each location over all time steps. Red solid circles show the locations of the sensors and the blue cross shows the estimated location of the PD source. The dashed circles show the location of the windings.

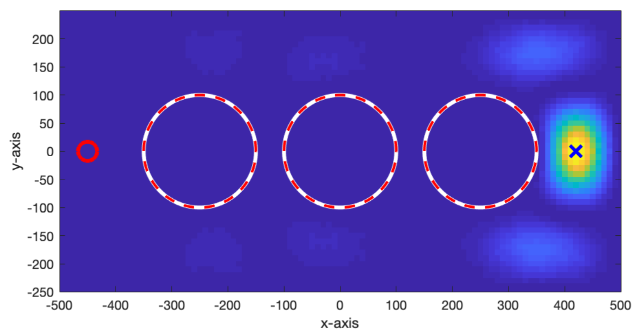



**FIGURE 4.** PD source localization by the EMTR technique using a single sensor. Normalized distribution of the maximum electric field power intensity at each location over all time steps. The red solid circle shows the location of the sensor and the blue cross shows the estimated location of the PD source. The dashed circles show the location of the windings.

## IV. SINGLE-SENSOR ELECTROMAGNETIC TIME REVERSAL PD LOCALIZATION

In this section, it is shown that the EMTR technique can yield the location of the PD source using only one sensor. The TDoA technique fails to provide any information on the PD location when one sensor is used.

### A. CASE STUDY 1: NO LINE OF SIGHT

The position of the sensor in this case study is shown with a red circle in Figure 4. The position, which is different from the positions of the sensors in the previously considered cases, was set in such a way that the line of sight to the PD source goes through all three windings, making the localization seemingly difficult. Figure 4 presents the results of the source localization by the EMTR technique using the single sensor. As can be seen, the EMTR method can provide the accurate position of the PD source even for the selected location.

### B. CASE STUDY 2: PD LOCATED BETWEEN TWO ADJACENT PHASE WINDINGS

In this section, a study is performed of the ability of the EMTR technique to localize a PD produced between two adjacent phase windings of the transformer, which is a critical location for electromagnetic based detection methods. A PD source location is defined as ''critical'' if the line of sight

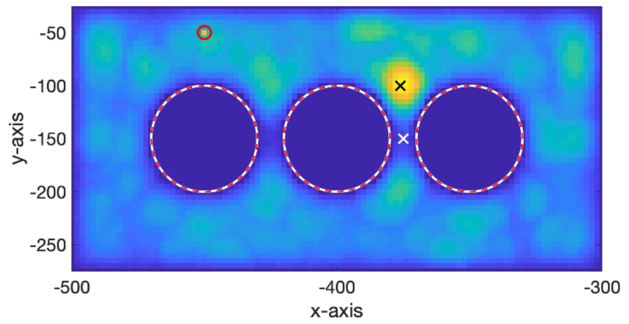



**FIGURE 5.** PD source localization by the EMTR technique using a single sensor when the PD source is between two adjacent phase windings and the spacing between the two adjacent phase windings is equal to 50 mm: Normalized distribution of the maximum electric field power intensity at each location over all time steps. The red circle, black cross, and white cross indicate the location of the sensor, the estimated location of the PD source, and the actual location of the PD source, respectively. The dashed circles show the location of the windings.

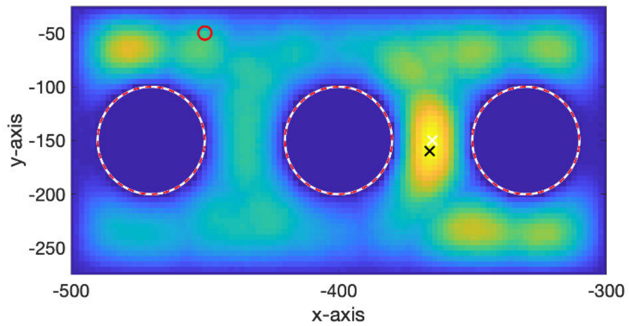



**FIGURE 6.** PD source localization by the EMTR technique using a single sensor when the PD source is between the two adjacent phase windings and the spacing between them is equal to 150 mm: Normalized distribution of the maximum electric field power intensity at each location over all time steps. The red circle, black cross, and white cross indicate the location of the sensor, the estimated location of the PD source, and the actual location of the PD source, respectively. The dashed circles show the location of the windings.

is obstructed and/or if the source is close to a conducting surface. Figure 1 shows the geometry of the problem with spacing $d$ between two adjacent phase windings. First, the EMTR procedure is applied when the spacing between two adjacent phase windings is 50 mm (corresponding to one half of the shortest wavelength of the source $\lambda_{min}/2$) and the distance between the PD source and the metallic winding is 25 mm ($\lambda_{min}/4$). Figure 5 shows the result of the PD source localization for the considered geometry and position of the PD source. The red circle shows the location of the sensor and white and black crosses indicate the actual and the estimated locations of the PD source, respectively. As it can be observed, the calculated location of the PD source exhibits a localization error of about 112 mm. The reason behind this large error lies in the distance between the PD and the winding, which is less than $\lambda_{\rm min}/2$. To further investigate the localization skill of the EMTR method, the EMTR procedure is applied to the geometry of Figure 1 with a spacing between two adjacent phase windings equal to 150 mm. In this case, the distance between the PD source and the winding is 75 mm. Figure 6 shows the result of the PD source localization using EMTR for this case. As it can be seen, the localization is much improved compared to the case with the shorter 50 mm spacing, with a localization error of 21 mm.

### *C. MONTE CARLO SIMULATION*

In order to study the influence of the location of the source in the performance of the EMTR technique for the location of PD sources, a Monte-Carlo simulation on 145 source locations is performed. The aim here is to examine if the method could work for various possible PD locations and to have an estimate on the statistical parameters of the localization error.

The nature of the time reversal solution procedure does not allow the use of analytical formulas. The Monte Carlo method was therefore used as a way of obtaining statistical information on the error through a random sampling of the possible PD locations.

The geometry of the problem is shown in Figure 1 of the paper with a winding spacing of 150 mm. Only sensor E1 was used. The x and y coordinates of the different locations of the PD sources in the Monte Carlos simulation were chosen randomly based on a uniform probability distribution within the tank.

It should be noted that the locations with distances less than $\lambda_{min}/2$ from metallic barriers were removed from the considered locations. Figures 7a and 7b provide the localization error along the x and y axes, respectively. In this case, the minimum, maximum, and mean values of the error are 2 mm, 108 mm, and 19 mm, respectively. These are based on the Euclidian distance between the estimated and the real locations obtained from the errors along the $x$ and $y$ axes.

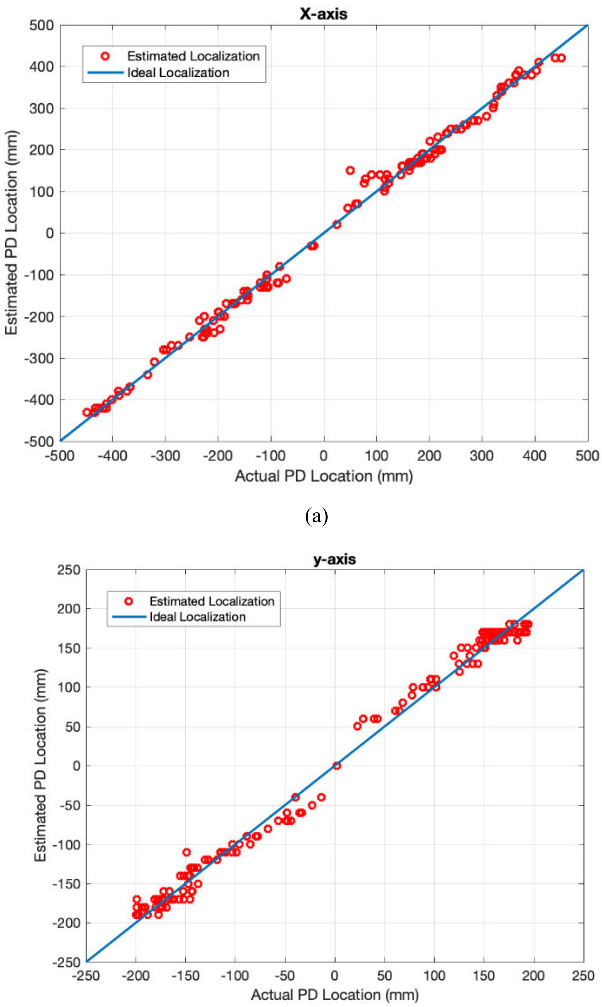
### *D. INFLUENCE OF THE NUMBER OF SENSORS*

In this subsection, the localization error in a scenario similar to the single sensor described above is investigated, the only difference being that two sensors are used: $E_1$ and $E_2$. The minimum, maximum, and mean values of the error in this case are, respectively, 2 mm, 34 mm, and 15 mm. Figures 8a and 8b provide the localization error along the x and the y axes, respectively. It can be seen that, by adding the second sensor, the maximum localization error was significantly reduced.

## V. EXPERIMENTAL VALIDATION

In this section, an experimental analysis of the ability of the EMTR process is presented for PD sources that are close to metallic objects. The EMTR process can be applied both in the time and in the frequency domains, in the latter case using the inverse Fourier transform to obtain the time signals. Here, an HP-8753D Vector Network Analyzer (VNA) is used to perform the experimental part of the time reversal process in the frequency domain.

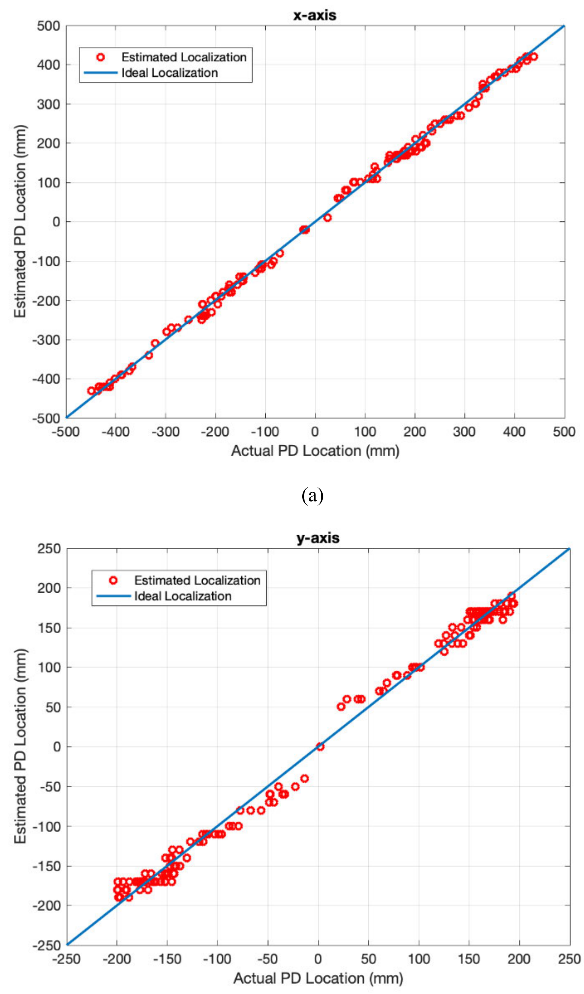
A metallic box with dimensions of $101 \times 73 \times 73$ cm$^3$ was used to represent the transformer tank. A monopole antenna with length 5.3 mm was used to emulate the PD source and another monopole antenna with length 8.3 mm was used as




(a)

(b)

**FIGURE 7. PD source localization using a single sensor. (a) Error along the x-axis. (b) Error along the y-axis.**




(a)

(b)

**FIGURE 8. PD source localization using two sensors. (a) Error along the x-axis. (b) Error along the y-axis.**

a sensor. The transformer tank, monopole antennas and a metallic object used to represent a transformer winding are shown in Figure 9.

The three-step procedure described in Section II is applied to locate the PD source: 1) Obtain forward time domain signal, 2) time reverse the signal and back inject it into the medium, 3) use the maximum field criterion to locate the PD source. To apply the procedure in the frequency domain:

- A Gaussian pulse with a bandwidth of 3000-MHz is considered and its Fourier transform is found. The time and frequency domain waveforms will be denoted as $x(t)$ and $X(\omega)$, respectively. The $S_{21}(\omega)$ response between the PD source and the sensor is measured using the VNA. Hence, the time domain field recorded by the sensor can be written as

$$r(t) = F^{-1}(X(\omega)S_{21}(\omega)),$$

  where the $F^{-1}$ operator is the inverse Fourier transform.
- In the time reversed step, $S_{12}(\omega)$ between the sensor and the test points is measured. Hence, the time reversed field in the time domain can be obtained as $E^{TR}(t) = F^{-1}(S_{12}(\omega))*r(-t)$, where $*$ is the convolution operator.
- In the third step, $E^{TR}(t)$ is calculated at each one of the test points to find the point with the maximum electric field.

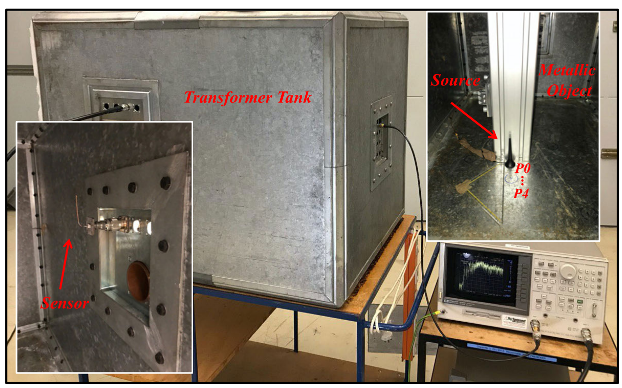



**FIGURE 9. Metallic box representing a transformer tank, monopole antennas and metallic object.**

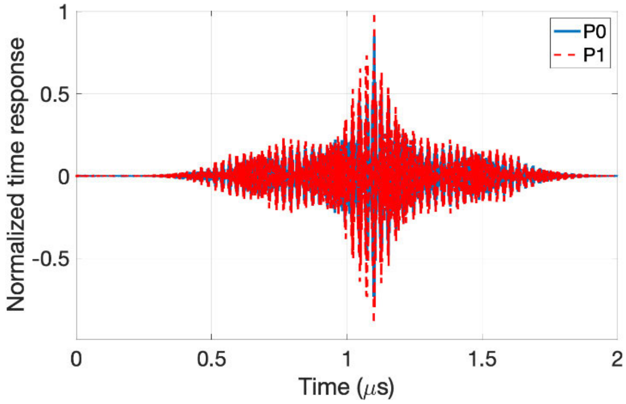



**FIGURE 10.** Time reversed field at locations $P_0$ and $P_1$.

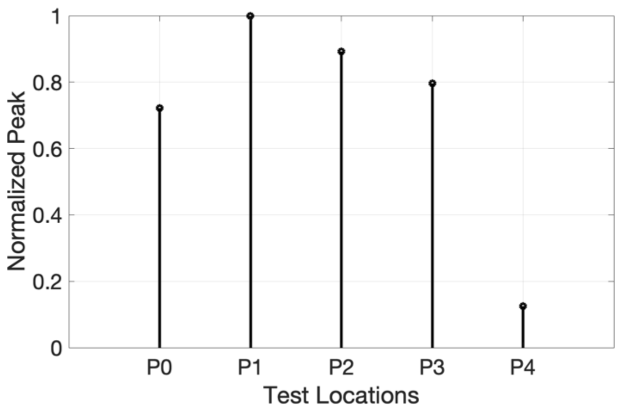



**FIGURE 11.** Normalized distribution of the peak time-reversed field at the test locations (source located at $P_0$).

It is worth mentioning that a limited number of test points is used in the third step due to practical limitations. It is indeed impossible to measure at all possible locations in space. Similar test procedures have been used by Fink and coworkers [26] to show the imaging ability of the TR process experimentally.

To investigate the effect of the vicinity to a metallic object, the PD source is considered to be at location $P_0$ (see Figure 9) and the test points $P_0$ to $P_4$, which are equally spaced at 1.5 cm to 5.5 cm distance from the metallic object, are considered. Note that the distance between $P_0$ and the metallic object (1.5 cm) corresponds to about 1/7 of the shortest wavelength of the source. Figure 10 shows the fields $E^{TR}(t)$ measured at $P_0$ and $P_1$. It can be observed that the peak field is higher at $P_1$ than at $P_0$. Therefore, the proposed method predicts that the location of the PD (which actually occurred at $P_0$) occurs at $P_1$, which represents a localization error of 1 cm. Figure 11 shows the normalized peak field of the time reversed field at all five test points.

To show that the method works when farther from the metallic object, the PD source location at $P_2$ (3.5 cm away from the object, corresponding to $\lambda_{\min}/3$) is considered now. Figure 12 shows the normalized peak electric field distribution of the time reversed field at all five test points. As it can be seen, the maximum normalized peak field value corresponds to $P_2$, which is the actual source location.

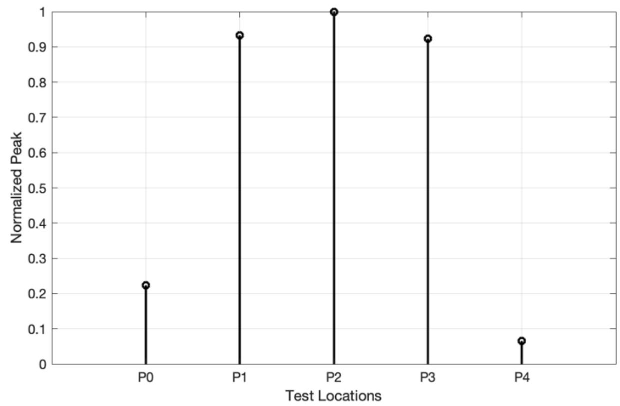



**FIGURE 12.** Normalized distribution of the peak time-reversed field at the test locations (source located at $P_2$).

It must be noted that the provided experimental results are a proof of concept for the applicability of the time reversal method to PD localization. Indeed, more thorough experimental validation is needed by considering a more realistic transformer, including an oil-filled tank and windings.

## VI. CONCLUDING REMARKS

In this paper, first, a theoretical comparison of the TDoA and electromagnetic time reversal techniques is performed when used for PD source localization. It is observed that, by using three sensors, the TDoA technique cannot provide accurate results when the line of sight is blocked by the presence of transformer windings. On the other hand, the electromagnetic time reversal technique can provide reasonable source localization results using only one sensor, even if the line-of-sight condition is not satisfied, barring the case where the PD source is closer to a metallic object than half of the minimum wavelength of the radiated field signal.

The skill of the proposed method to localize PD sources in the vicinity of metallic objects is analyzed both numerically and experimentally. It is observed that, although a degradation in the accuracy of the localization is observed compared to the case of longer distances between the PD source and the metallic object, a reasonable localization error of 10 mm (corresponding to $\lambda_{\min}/10$) is obtained.

In summary, the presented numerical simulations supported by experimental results suggest that the electromagnetic time reversal method is capable of providing accurate localization of PD sources occurring at distances further than the diffraction limit ($\lambda_{\min}/2$) to metallic objects such as the surface of the power transformer tank or the windings.

2D configurations were used in this paper to demonstrate the ability of the time reversal technique to perform non-line-of-sight localization of PD sources. Future work is underway to investigate the performance of the time reversal technique to locate PD sources in realistic (3D) transformers.

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