NEW METHODS FOR MULTISOURCE PD LOCALIZATION ON POWER TRANSFORMERS BY AN ACOUSTIC SENSOR ARRAY

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Abstract: Classical acoustic partial discharge (PD) localization methods are limited to the detection of a single PD source. In this contribution an ultra-high frequency antenna is used to trigger an acoustic planar uniform linear sensor array for the localization of multiple PD sources. The usually applied method for noise reduction, the averaging of sequent signals, is limited to one single PD source. Because of noise corrupted environments, alternatives for the averaging method are needed to detect weak acoustic signals, even below noise level. The applicability of various digital filters for noise reduction is investigated, and the suitability of different methods for arrival time detection of acoustic PD signals is determined. Laboratory measurements show the accuracy of localization with an acoustic sensor array triggered by an ultra-high frequency antenna. Furthermore, the ability of this measurement system to locate multiple PD sources simultaneously is shown.

1 INTRODUCTION

Partial discharges (PD) in transformers are an indication for an existing degradation of the insulation material. A possible consequence of this can be a progressive damage of the insulation system, resulting in extensive damage or even failure of the transformer. To prevent this, the PD activity can be monitored permanently in power transformers. Optionally, a maintenance or repair can be arranged if indicated by the PD monitoring [1]. The knowledge about existence, extent and especially the position of PD can help to determine the state of the transformer. If a repair is indicated, the position of PD in the transformer is helpful in order to find the affected area in the insulation. Especially in environments with high noise level or in case of multiple PD sources conventional detection methods based on the averaging method fail [2]. Therefore, new methods for noise suppression and automatic run-time determination are required.

2 SENSOR ARRAY APPROACH

The localization is based on the combination of an ultra-high frequency (UHF: 300 MHz – 3 GHz) measurement of electromagnetic radiation and run-time determination of ultrasonic emissions, both generated by the PD source. Hence, an UHF drain valve sensor [3] is inserted via a standardized flat wedge valve into the power transformer. The measured UHF signals propagate with about 2/3 the speed of light in the insulation oil. They can be used to trigger an acoustic measurement and to determine the run-times of acoustic signals, which only have a velocity of about 1400 m/s in transformer oil. If there is no suitable valve for UHF sensors, the electrical PD measurement according to IEC 60270 can be used as alternative trigger for the acoustic localization. A decisive advantage of the UHF method is its insensitivity to external corona discharges, which represent the highest potential of interference for the electrical measurement. The UHF sensor is located inside the transformer tank with its electromagnetical shielding effect (Faraday cage) as shown in Figure 1. Thus the UHF technique is less sensitive to external electromagnetic interferences.

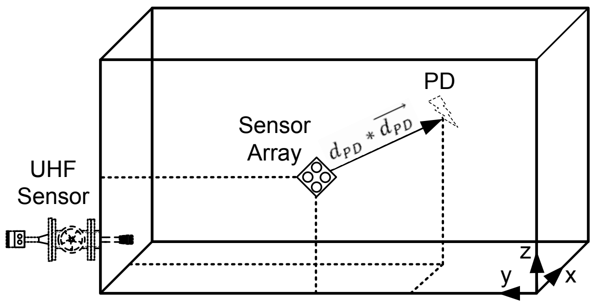

Figure 1: Measurement setup for PD localization

For PD source localization an acoustic sensor array is used, consisting of 4 acceleration sensors having a resonant frequency of f_R = 150 kHz. This uniform linear array (ULA) [4] consists of two acoustic sensor pairs, which are arranged in a 90° angle to each other, as sketched in Figure 1. For localization via run time differences a total minimum of three sensors is required. In this contribution, the localization principle is shown with four sensors, which are mounted in a crosswise arrangement on the transformer. The distance between the sensors is d = 11 cm.

2.1 Distance Calculation

The distance between PD and sensor array can be determined by the time Δt between UHF signal (or IEC signal) and the acoustic signals. The run time of electromagnetic waves is negligible compared to the run time of acoustic waves; hence the UHF triggers the run time measurement of acoustic signals. From the four individual run times of each acoustic sensor, the mean value is calculated to obtain the propagation time to the array centre. This duration is multiplied by the propagation velocity of ultrasound in oil according to equation (1) to calculate the distance between PD and sensor array [4]. It has to be considered that the velocity is oil temperature dependent [5].

$$d_{PD} = \Delta t * v_{oil} \tag{1}$$

The exact start time of the acoustic signals are either determined by the energy criterion [2], by a spectroscopy, a matched filter or a matched filter bank. These methods are described in detail and their accuracy compared in chapter 4 of this contribution.

2.2 Angle of Incidence Calculation

To determine the angle of incidence Φ_{ULA} the delay differences t_{delay} between the sensors are required. For this purpose, the individually calculated starting times of the sensors can be used depending on their accuracy. In addition, the starting time difference can be determined via cross-correlation of the sensor signals. In Figure 2, the determination of the angle of incidence by transit time difference between two sensors can be seen.

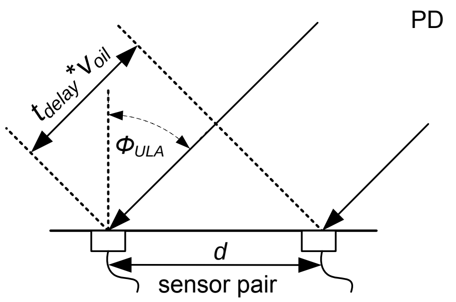

Figure 2: Angle of incidence determination

The angle of incidence Φ_{ULA} is calculated according to formula (2) [4].

$$\Phi_{ULA} = arcsin\left(\frac{t_{delay} * v_{oil}}{d}\right) \tag{2}$$

This angle results in an ambiguous cone surface around the sensor axis. An acoustic wave of a PD has its origin at any point on the cone surface in Figure 3. The sensor array consists of two pairs of sensors. For each pair of sensors an incident angle is calculated, thus for each sensor axis an ambiguous cone surface is determined. These intersect in exactly one projection line, which is located on the PD source [4].

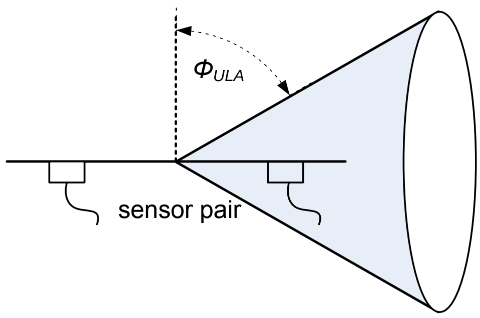

Figure 3: Ambiguous cone surface

The normalized line of intersection represents the direction $\overrightarrow{d_{PD}}$ from the sensor array to the PD, see Figure 1.

2.3 Localization of the PD

To indicate the location of the PD source the array position is needed in addition to the calculated distance and the determined direction. According to formula (3) the location of the PD is calculated by a vector addition in the transformers' coordinate system defined in Figure 1 [4].

$$\overrightarrow{PD} = \overrightarrow{Array} + d_{PD} * \overrightarrow{d_{PD}} \tag{3}$$

3 DISTURBANCES AND FILTERING

The accuracy of the localization strongly depends on the signal's quality. Superimposed noise can produce erroneous results. The noise level varies strongly depending on the environment and can even exceed the acoustic signal amplitude. In previous localization methods noise was reduced by an averaging of many sequent PD signals. The averaging of sequent emissions from different sources results in the interference of incoherent signals. Thus, for the localization of multiple PD sources averaging is not applicable.

3.1 Noise Models

To investigate the performance of implemented algorithms, noisy signals are needed. Therefore existing low-noise signals from laboratory measurements are superimposed to different noise models. On the one hand, white Gaussian noise and on the other hand a type of colored noise. It is generated from the white noise, but it only has frequency components up to 100 kHz. This provides a good approximation of measured noise spectra of power transformers [6]. Figure 4 shows an acoustic PD signal (red) and the same signal with superimposed colored noise (blue).

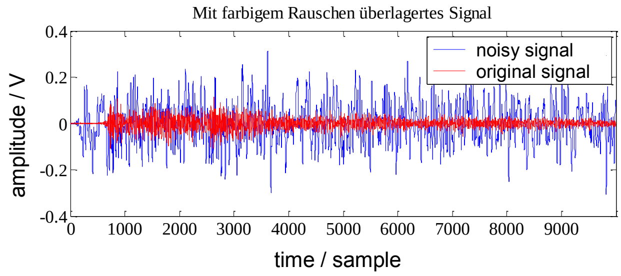

Figure 4: Superposition of acoustic PD signal and colored noise, being typical at transformer sites

3.2 Adaptive Prediction

The signal s[n], consisting of the wanted signal x[n] and noise r[n] is led to the "desired" input d[n]. It is also led to the reference input, delayed with D samples s[n-D]. This adaptive filter structure is often referred as a decorrelator. The reason for this structure (see Figure 5) is the assumption that the noise r[n] is broadband and random and not correlated with its delayed signal r[n-D]. However, x[n] is a "slow" time signal and strongly correlated with its delayed signal x[n-D].

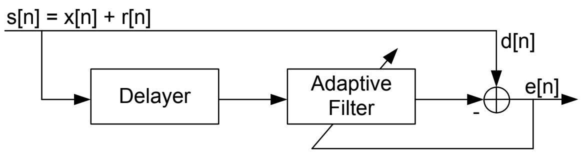

Figure 5: Adaptive LMS filter

The adaptive filter attempts to keep the cost function e[n] (signal s[n] minus adaptive filter output) minimal. The algorithm used is called Least Mean Squares (LMS). The cost function is squared and the filter parameters are adjusted in order to minimize the squared error. For random signals s[n] generally D = 1 is used in the delayer.

3.3 Wavelet Filter

A wavelet noise filter algorithm transforms the time signal into frequency domain, removes unwanted signal components (noise) due to processing of wavelet coefficients and transforms the reconstructed signal back to time domain. The most important step is the estimation of the filter coefficients. Here different estimation methods are applied. Figure 6 shows wavelet noise filtering with different estimation procedures.

The Universal Thresholding [7] removes noise, but the reconstructed signal is very inaccurate. The filtered signal with SureShrink [7] looks very similar to the original signal, but has hardly any reduction of noise. The reconstructed signal estimated with VisuShrink [7] resembles the original signal best and has significantly reduced noise.

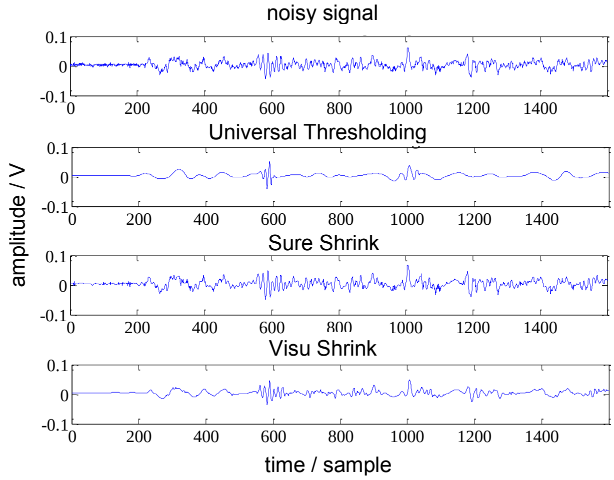

Figure 6: Results of different estimation methods

4 START TIME DETERMINATION

An important component of the localization system is a reliable automated start time determination of the acoustic signals of the sensor array.

4.1 Energy Criterion

The Hinkley method or energy criterion is a classic method for start time determination of acoustic PD signals [2]. It is the simplest implemented detection method with the least amount of computational effort. A negative trend is subtracted from the cumulative signal energy. The Hinkley function is defined as:

$$S_i' = \sum_{k=0}^{i} (x_k^2 - i\delta) \qquad (4)$$

Once the signal energy exceeds the negative trend the Hinkley function gets a low point. As the

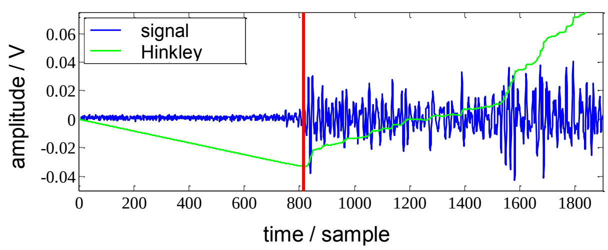

Figure 7: Principle of Hinkley function for signal start time determination via signal energy content

4.2 Spectroscopy

Spectroscopy is oriented to the spectral composition of the signal and not its energy content. With a short-time Fourier transformation (STFT), the signal is transformed into a time-resolved frequency domain. An analysis of the typical PD frequency component of f = 150 kHz (the resonant frequency of the sensor) is used for start time detection. Important in the STFT is the width of the cutting window in time domain. The STFT cannot obtain an arbitrarily high resolution of time and frequency, due to the uncertainty principle of signal processing. A higher frequency resolution has a lower time resolution as result and vice versa. The window must therefore be chosen sufficiently short in order to obtain an adequate time resolution for the detection of the starting time. Figure 8 shows two spectrograms of the signal from Figure 7.

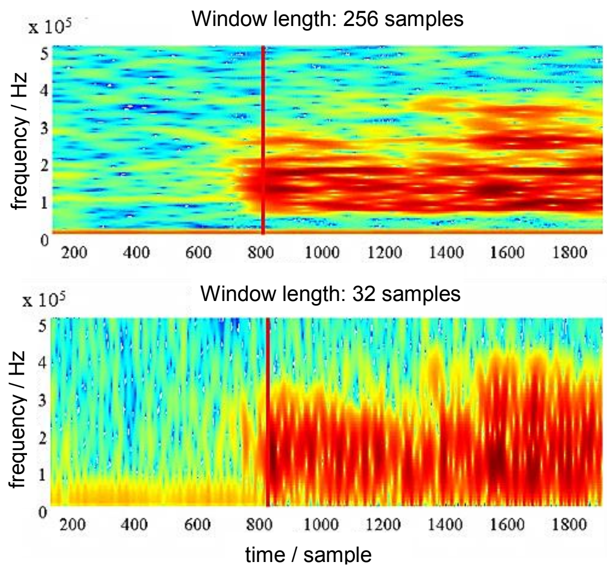

Figure 8: Spectroscopies with windows of different lengths

The first peak in the typical PD frequency component is used as a starting point (red). The time shift by half the sample length of the window is already taken into account. It is apparent that a longer window can cause an erroneous detection to the start time. Signal start is at 820 samples. The upper spectroscopy recognizes a too early starting time at 800 samples, whereas the lower spectroscopy, having a short window length, delivers a correct signal start.

4.3 Matched Filter

Matched filters are based on the signal shape of a PD pulse. As long as the shape of different PD pulses is similar, matched filters can detect the correct start time even with extremely noisy signals. The filter is based on a reference signal, which represents a typical PD pulse. A study of different examined signals shows a Gaussian modulated sine wave at f = 150 kHz proved as a very suitable reference signal. This reference signal is searched by the filter in the acoustic signal by means of cross-correlation. Figure 9 shows the correlation (blue) of the signal in Figure 7 with the reference signal. The first peak from the correlation is selected as start time (red).

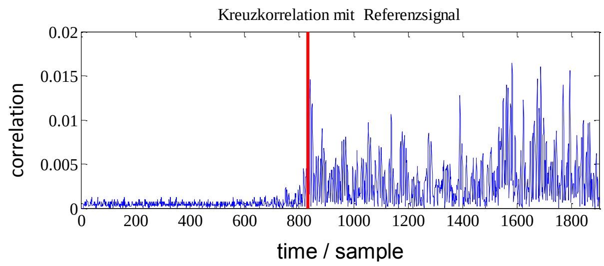

Figure 9: Correlation of matched filter

4.4 Matched Filter Bank

A matched filter bank (MFB) is based on the described matched filter above. It consists of a reference signal database, compared as previously by cross-correlation with the original acoustic PD signal [8]. Figure 10 shows the structure of such a MFB with three exemplary reference signals. It includes Gaussian modulated sine waves in the frequency band of 100 kHz – 150 kHz in 10 kHz steps.

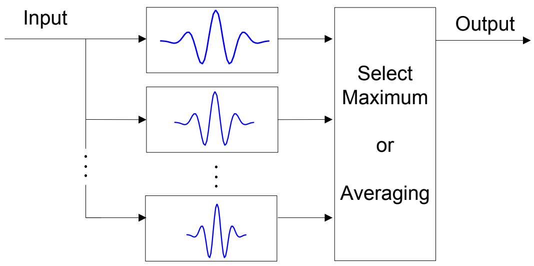

Figure 10: Structure of matched filter bank

At the MFB output either the correlation with the highest degree of correlation is selected, or a mean correlation can be calculated by averaging. Thereafter, as in the single matched filter, the start time is detected by a threshold value or Hinkley criterion.

4.5 Consistency and Correction

The difference between the start times, detected by each single sensor is limited to a maximum of 80 µs, according to the distance between the sensors of 11 cm. If the time delay exceeds this limit, the detection wasn't successful. This dependency is used for a consistency check. Figure 11 shows a consistency based correction.

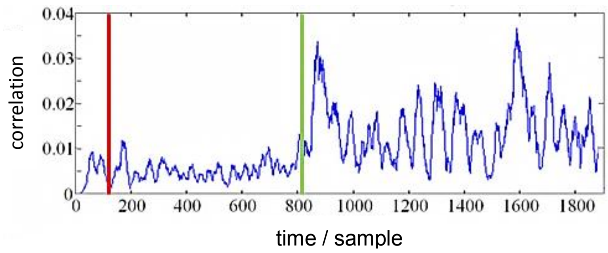

Figure 11: Start times before and after correction

In Figure 11, a matched filter correlation with wrong detected start time (red) and the corrected result after the consistency check (green) can be seen. Especially with high noise, an often seen fault is an erroneous early detection of start times. When an inconsistency is detected, an early start time is dropped and is searched again in the range of the start times of the other three sensors.

5 ANGLE OF INCIDENCE ESTIMATION USING CROSS CORRELATION

Based on starting time differences of the ultrasonic signals the angle of incidence of a wave front can be determined. For this purpose the difference between two pairs of starting times is needed in a very high accuracy. The angle calculation is often not sufficiently accurate, when the starting times detected by previously presented methods are used. Remedy provides a cross-correlation with the signals of the individual sensors, according to formula (5). This takes advantage of the fact that the signal shapes are very similar, because the sensors in the array are close to each other.

$$r_{xy}(n) = \sum_{m=-\infty}^{\infty} x(m) * y(n+m) \qquad (5)$$

Because the cross-correlation has a high computational effort, its application is useful only in a small signal section around the previously detected starting time. The function $r_{xy}(n)$ describes the similarity of a signal x(m) to the by n samples time-shifted signal y(n+m). At the highest similarity $r_{xy}(n)$, n corresponds to the start time difference.

6 LOCALIZATION RESULTS

This chapter describes two laboratory measurements with the presented UHF-acoustic PD localization system and the methods discussed in previous chapters. The measurements were carried out in an oil-filled 50 cm x 100 cm x 50 cm steel tank. Two PD sources are inserted, which can be moved and energized independently of each other. Figure 12 shows the test tank with the attached acoustic sensor array. The PD sources are located inside the oil.

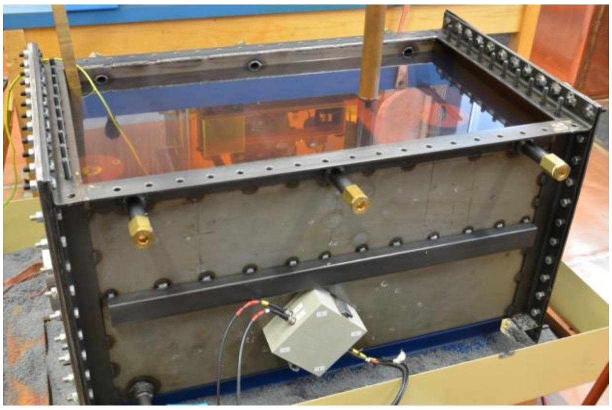

Figure 12: Experimental tank with sensor array

6.1 Comparison between Angle of Incidence Calculation Methods

Two methods for determining the angle of incidence are compared in laboratory experiments. On the one hand the angle determination based on the detected starting times and on the other hand the angle calculation based on cross-correlation. The start times are calculated using Hinkley criterion and are identical in both cases. Figure 13 shows the angle determination made by detected start times. In Figure 14, the angle calculated using cross-correlation is shown in a top view on the experimental tank.

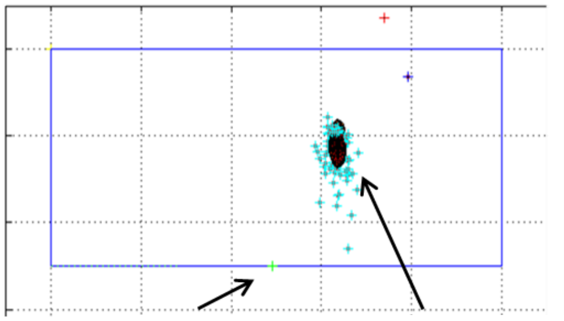

Figure 13: Localization result using starting times

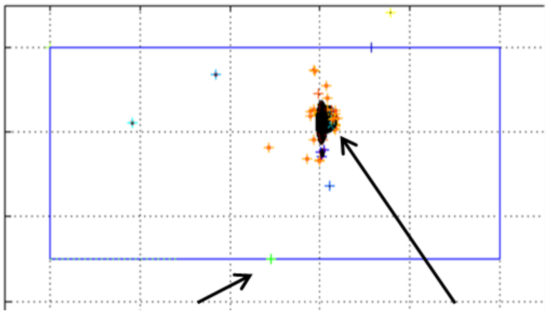

Figure 14: Result using cross-correlation

Table 1 shows that in this example, cross-correlation based localization is significantly better with a deviation of only 2.1 cm, while in the other method, the deviation using start times is around 14 cm.

Table 1: Comparison between angle of incidence calculation methods

	x /cm	y /cm	z /cm	P_i	D /cm
array	50	49	36		
PD origin	15	62.5	24		
Result using:					
start times	21.76	63.68	15.90	80%	14.09
cross-correlation	16.75	61.63	23.19	83%	2.12

Considering the small size of the experimental tank and the fact that it is only filled with oil, and no active part is inside, a sevenfold difference is unacceptable. In both cases the system recorded 300 PD events. x, y and z are the coordinates in cm, P_i is the percentage of the corresponding localizations which lie in the cluster, and D is the deviation of the center point of the cluster to the actual PD source position in cm. In general, the cross-correlation is more accurate and gives better results in various laboratory measurements with noisy signals. In case of very precise start times, for example because of low noise, an angle determination based on the start times can be computed faster than based on cross-correlation.

6.2 Localization of Multiple PD Sources

The aim of the presented system is the localization of multiple PD sources within a transformer based on single-shot measurements. The laboratory measurement shows a successful localization of two PD sources simultaneously. Figure 15 shows a graphical representation of the localization in a top view of the laboratory tank.

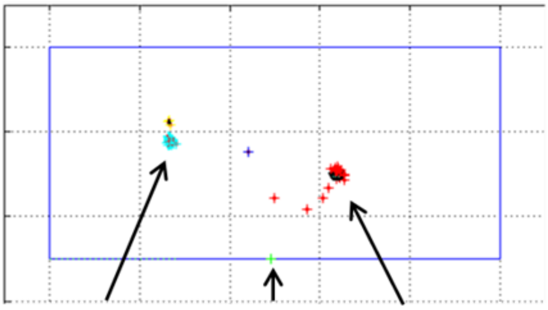

Figure 15: Localization with two PD sources

In Table 2, the combined results of the measurement with two PD sources, and the deviations of the measuring system to the actual position of the PDs are shown.

Table 2: Results of PD localization with two PD sources

	x /cm	y /cm	z /cm	P_i	D/cm
Array	50	49	36		
PD 1	22	26	17		
PD 2	28	65	23		
Cluster1	24.60	44.16	28.40	0.03%	-
Cluster2	22.14	26.79	19.32	70,3%	2.38
Cluster3	17.58	26.49	40.59	1%	-
Cluster4	29.77	63.81	27.33	28,3%	4.83

PD source 1 is more active than PD source 2, which means it produces in the same time significantly more UHF and acoustic signals than the other source. Nevertheless both PD sources can be clearly seen and are distinguishable from the few false detections (clusters 1 and 3). The distance is determined by Hinkley and the angle of incidence by cross-correlation. The deviations from the actual PD positions are low and confirm that accurate localizations of multiple PD sources is possible simultaneously with single-shot measurements.

7 CONCLUSION

The aim of the presented measuring system, consisting of a UHF sensor for triggering and an acoustic sensor array, is the localization of multiple partial discharge sources within a transformer tank. The necessary methods for noise reduction, and start time determination are shown in this contribution. The presented laboratory measurements show that the system is able to locate multiple partial discharge sources simultaneously with high precision. Further investigations on multisource PD localization on real power transformers will determine the ULA system in practice.

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