Computer Applications in Electrical Engineering
Vol. 13 *2015*

Prototype measurement system for localization of partial discharges sources – microphone array

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This paper presents a prototype measurement system, that will be used for localization of acoustic emission sources originating from partial discharges (PD). It is based on sensor arrays technology and direction of arrival estimation algorithms. Acoustic signals will be received with a universal linear array (ULA) of sensors, wherein the sensory elements are microphones operating in the audible frequency range. For the estimation of the direction of arrival of these signals conventional beamforming algorithm is used which has also been described theoretically. Ultimately, the system will be used to determine the direction of arrival of the acoustic signal generated by the insulation defect, which is corona discharge.

KEYWORDS: partial discharges (PD), PD localization, sensor array, microphone array, beamforming, direction-of-arrival (DOA)

1. Introduction

Issues relating to the detection, identification and localization of partial discharges (PD) sources are currently the subject of extensive research aimed at improvement of the reliability of currently used diagnostic and monitoring methods of power transformers based on the detection of PD phenomenon [1-6]. Authors' research focuses on finding new theoretical and technological solutions that would greatly improve the accuracy of location of defects in high voltage insulation system.

A major problem are also structural defects or installation faults of protruding power transformer components that may be causing corona discharges or discharges arising on the soiled surface of the bushings. This problem also applies to new units, where during acceptance tests, as a result of bad shielding of electromagnetic fields, on sharp elements corona discharges may appear.

Assuming that the acoustic signal generated by corona discharges is a wideband signal, discharges are being localized most frequently with ultrasonic directional microphones. This solution is however rather vague and largely dependent on the experience of the person performing the measurement.

Concept presented in previous articles [9, 10] presupposes the application of sensor array technique to estimate the direction of arrival (DOA) of acoustic emission (AE) signals or electromagnetic pulses originating from PD.

This article expands hitherto presented solutions with application of Delay-and-Sum beamforming algorithm which, by virtue lesser degree of sophistication (small computational complexity) is an alternative to a high resolution DOA estimation algorithms, such as MUSIC, Root-MUSIC, ESPRIT, etc.

In addition to the theoretical description, a prototype measurement system that uses sensor arrays (with omnidirectional microphones as sensory elements) is described. In further part of this article test measurement results are presented.

2. Beaforming

Beamforming methods are based on space-time processing of the signal detected by the microphone array. Amplitudes and phases of acoustic signals received by each element of the array are being analyzed to yield the correlations between these signals. The second part of this article will consider a case with use of a uniform linear array (ULA) of sensors which principles were described in details in [9].

The base concept of beamforming is to perform measurement with an array in a predetermined direction and calculate the signal strength. When the set direction coincides with the actual direction of arrival of the signal, the highest value of output power can be seen [11, 12].

Current state of knowledge on signal analysis allows to virtually “steer” the array through appropriate design of the so-called “steering vector”. To linearly combine the data received by the array elements to form a single output signal $y(t)$, a weight vector **w** is designed based on previously defined steering vectors. Different beamforming techniques use different weight vectors **w.**

$$y(t) = \mathbf{w}^H x(t) \, . \tag{1}$$

The total averaged output power out of an array over N snapshots can be expressed as:

$$P(\mathbf{w}) = \frac{1}{N}\sum_{n=1}^{N}\left|y(t_n)\right|^2 = \frac{1}{N}\sum_{n=1}^{N}\mathbf{w}^H x(t_n) x^H(t_n)\mathbf{w} \, , \tag{2}$$

where $\frac{1}{N}\sum_{n=1}^{N} x(t_n)x^H(t_n)$ can be expressed as $\mathbf{R_{xx}}$, which is an estimated covariance matrix, so finally the total output power of the array can be defined as:

$$P(\mathbf{w}) = \mathbf{w}^h \mathbf{R}_{\mathbf{xx}} \mathbf{w} \, . \tag{3}$$

In most widely used algorithm, the Delay-and-Sum (DAS), the weight vector is obtained from the following formula:

$$\mathbf{w} = \frac{\mathbf{a}(\theta)}{\sqrt{\mathbf{a}^H(\theta)\mathbf{a}(\theta)}} . \tag{4}$$

The steering vector **a**(θ) is similarly defined for any observation angle θ:

$$\mathbf{a}(\theta) = [1 \quad e^{j\mu_i} \quad e^{j2\mu_i} \quad \cdots \quad e^{j(M-1)\mu_i}]^T , \tag{5}$$

where:

$$\mu = -\frac{2\pi f_c}{v} \Delta \sin\theta = -\frac{2\pi}{\lambda} \Delta \sin\theta , \tag{6}$$

with f_c being the analyzed frequency, v – signals propagation speed, Δ – array element spacing and θ – currently "scanned" angle.

By inserting the weight vector equation (4) into (3), the output power as a function of angle of arrival, or termed as spatial spectrum, is obtained as:

$$P(\theta) = \frac{\mathbf{a}^h(\theta)\hat{\mathbf{R}}_{\mathbf{xx}}\mathbf{a}(\theta)}{\mathbf{a}^H(\theta)\mathbf{a}(\theta)} . \tag{7}$$

3. Prototype measurement system – microphone array

Corona discharges generate sound signal in wide range of frequencies, e.g. in audible band, therefore microphones used in array should have a flat frequency response in range 20 Hz – 20 kHz and an omnidirectional polar pattern. Superlux ECM-999 free-field measurement microphones (Fig. 1) are able to match those requirements, which were also used to build the array.

Fig. 1. Single Superlux ECM-999 microphone with HM-10B stand mount

To acquire signals from each microphone, 8-channel M-Audio ProFire 2626 audio interface was used (Fig. 2). It delivers sampling rates up to 192 kHz and high bit depth (24-bit). ECM-999 microphones are connected with the ProFire interface with a professional 8-way wire The Sssnake SXX8050.

Fig. 2. M-Audio ProFire 2626 audio interface

Figure 3 presents the schematic diagram of designed measurement system, which operates in frequency range from 20 Hz to 22 kHz. The use of microphones at the conceptual measurement system allows for some flexibility in the design of the array itself. It is possibile to check the efficiency of an array with use of different number of sensors (microphones) or different apertures (e.g. linear, rectangular etc.).

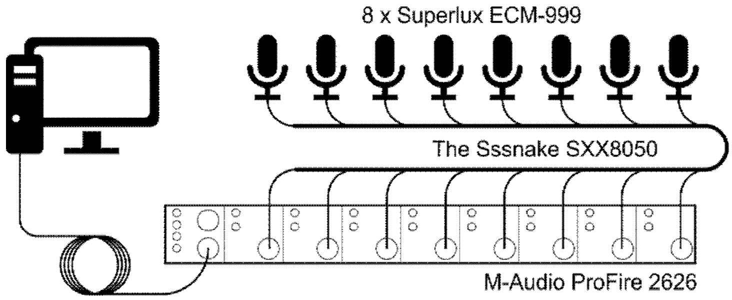

Fig. 3. Schematic diagram of designed measurement system

Due to a combination of sensor array technique and beamforming algorithms it is possible to estimate the direction of arrival of the incoming acoustic signal. The array is set in different positions relative to the sound source. Obtained results are then compared with the preset values.

4. Signal source localization – simulation and measurements results

The basic parameter, that describes sensor arrays is their directional characteristics. As it was mentioned in chapter 3., a single array element should have an omnidirectional polar pattern. Due to a combination of two or more elements, which are taken to build an array, a specific characteristics is being created. Directionality indicates how sensitive it is to sounds arriving at different angles about its central axis (Fig. 4).

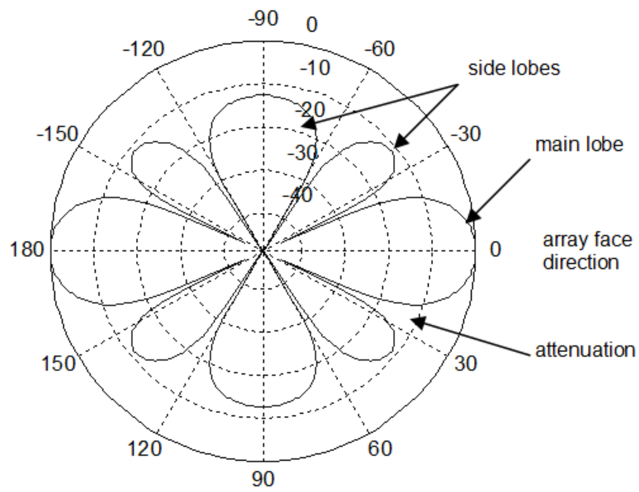

Fig. 4. Directionality of a 4-element microphone array, for the elevation angle of 0°
(f = 2000 Hz, Δ = 10 cm, θ = 0°)

Assuming, that the signal propagation speed is constant, array polar pattern may vary depending on three parameters:

– frequency of the signal,
– number of elements in array,
– array elements spacing [7, 8].

Depending on those parameters example polar patterns were created in MATLAB (Fig. 5, 6 and 7).

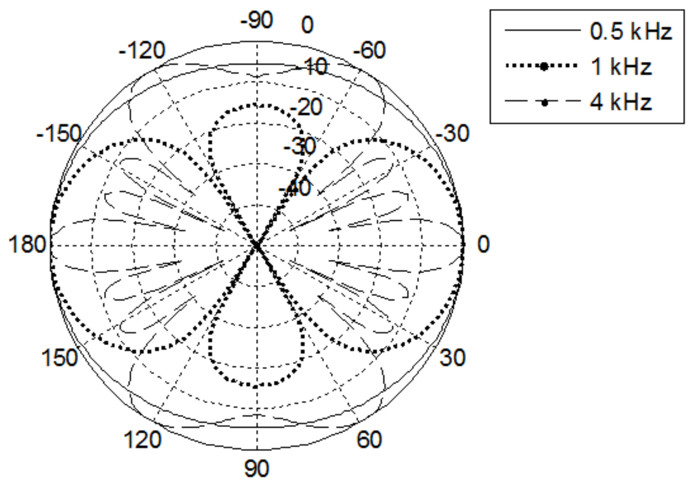

Fig. 5. Example of polar pattern of 4-element linear microphone array (Δ = 10 cm) depending on different signal frequencies

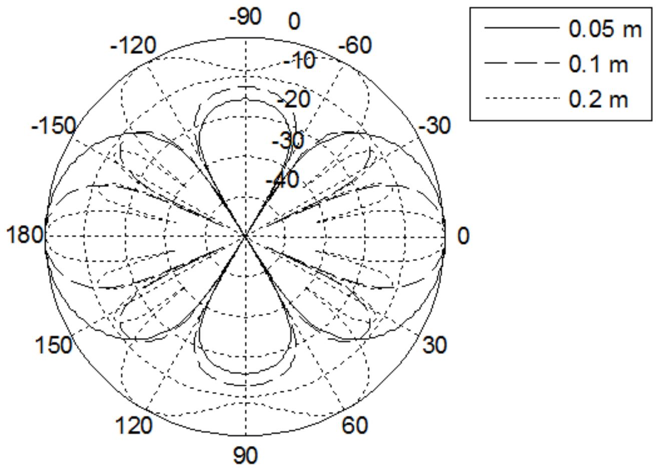

Fig. 6. Example of polar pattern of 4-element linear microphone array (*f* = 2 kHz) depending on different element spacing

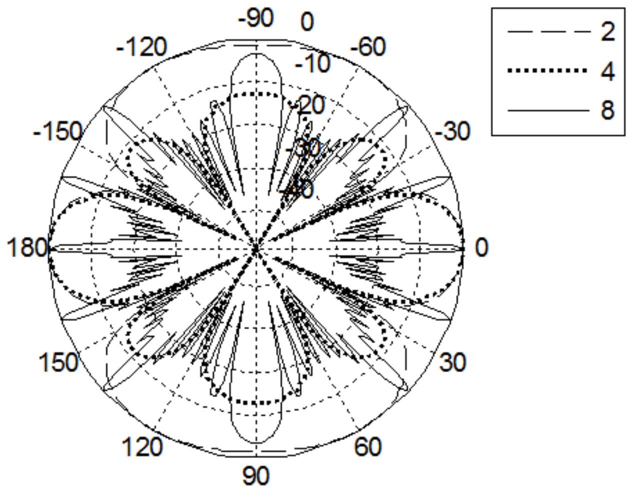

Fig. 7. Example of polar pattern of a linear microphone array build with 2, 4 and 8 microphones (constant total width and *f* = 2 kHz)

The first test was conducted to verify the correctness of algorithms. For this purpose, the array was set at a predetermined angle relative to the speaker with which the signal was generated. The array consisted of 8 microphones and the distance between them was 21 mm. Then, based on the recorded waveforms, the DOA angle was determined, and then compared with set value. In parallel a simulation was also conducted, which provided the same scenario. Example results are illustrated in Figure 8.

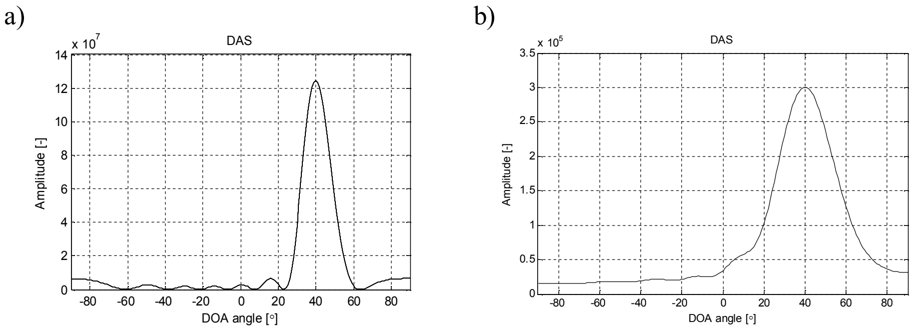

Fig. 8. Comparison of estimated DOA angles obtained by (a) simulation and (b) measurements

The next step was an attempt to localize the source of corona discharges. For this purpose a high-voltage board-edge circuit was used, wherein the corona discharges were generated. To perform the localization at least two sensor arrays must be used, so that the intersection point of two lines, led at designated angles from the center of the arrays, will determine the source location [13], therefore two 4-element microphone arrays were build with 21 mm spacing between elements. Arrays were set at a distance of 40 cm from each other, and 3 m from the HV discharges generation system. For the zero point half the distance between the arrays was chosen. After performing the signal registration, the measurement system was shifted 25 cm to the right. Every sample was 5 s long, and was recorded with 96 kHz sampling frequency. The simplified measurement procedure is presented in Figure 9.

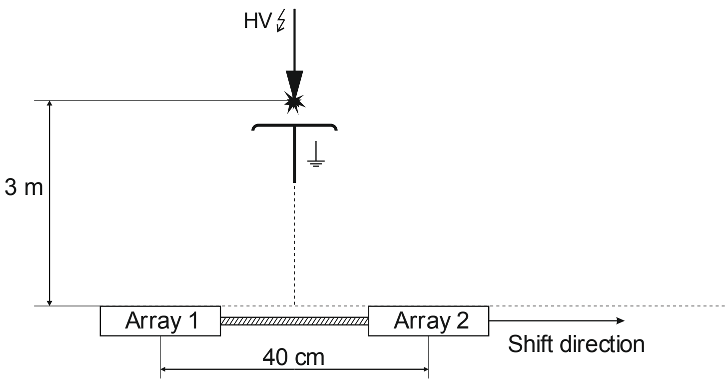

Fig. 9. Simplified measurement procedure

Localization results are presented in figures 10 to 12. DOA estimation was performed for 5 frequencies. Real coordinates of the source are given on the description below the figure.

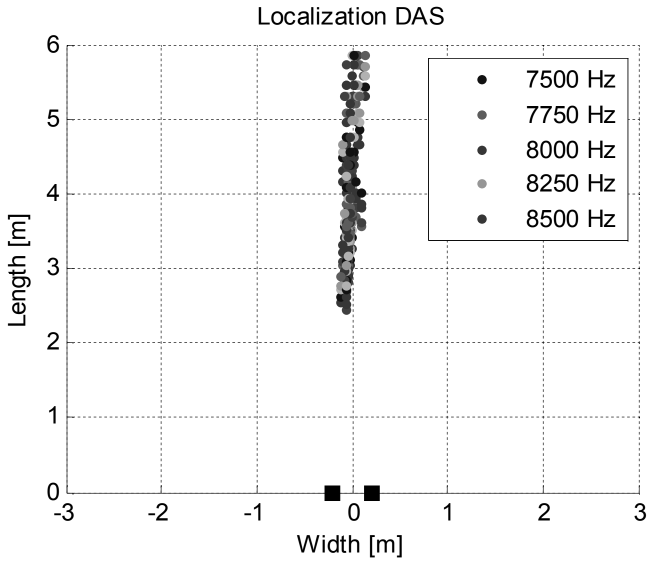

Fig. 10. Corona discharges source localization results. Real coordinates: (0.0, 3.0)

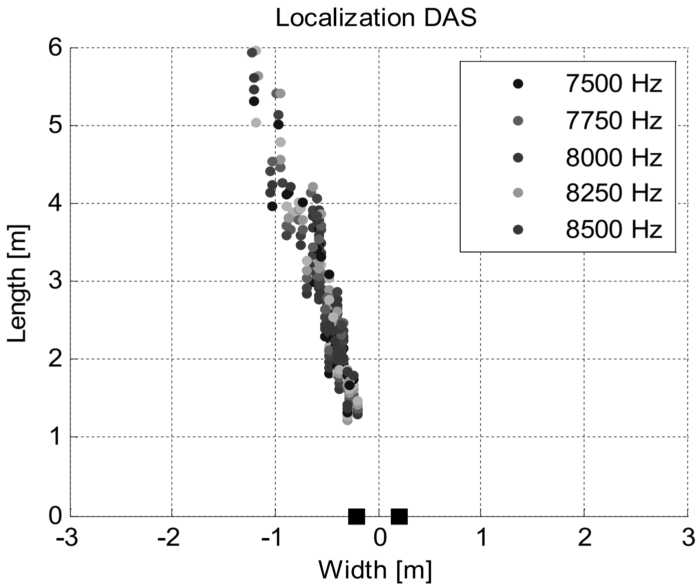

Fig. 11. Corona discharges source localization results. Real coordinates: (0.5, 3.0)

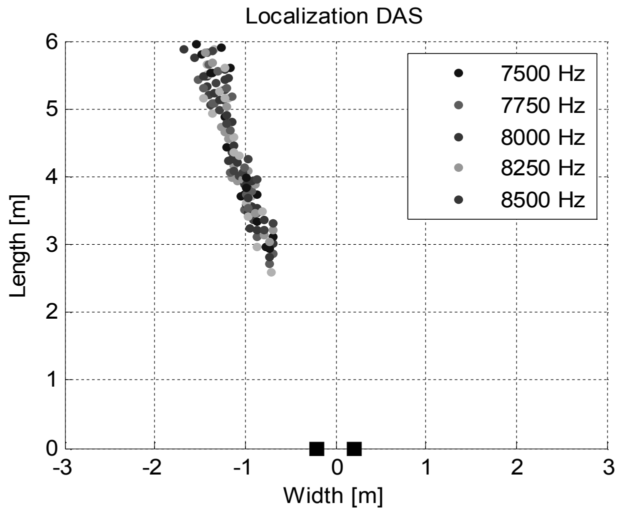

Fig. 12. Corona discharges source localization results. Real coordinates: (1.0, 3.0)

Every analysis was performed at 2048-samples snapshots, along whole recorded signal. Such procedure results in obtaining a “cloud” of locations, where the signal source could be localized.

5. Conclusion

Sound sources localization with use of microphone arrays and beamforming algorithms is a technology widely used e.g. in automotive industry (to determine “noisy” parts of vehicles) or in environmental surveys to create acoustic maps.

The concept of a prototype measuring system presented in this article may find application in localization of corona discharges, that occurs e.g. near bushings of power transformer as a result of, among others, design flaw, material defects or bad fit of the transformer elements. Such scenario usually occurs during acceptance tests of transformers. In this situation occurrence of corona discharges is highly undesirable, therefore localization of such spots could speed up the diagnostic procedures, countermeasures application and final hand over.

As seen above, the function of determining source coordinates is working properly. Accuracy is limited, which is particularly noticeable for the most distant source position relative to measurement system. The cause of the low accuracy can be the broad power spectrum density of the signal coming from the corona discharge.

The most important aspect remains the appropriate design of the measurement system, that is arrays themselves, their reciprocal setting in regard to the test object. Arrays should be so arranged that the test object will be located within their angular range of proper operation.

In parallel with studies presented in this paper a survey over use of sensor arrays for internal PD localization is conducted.

This article was financially supported within the project "Engineer of the Future. Improving the didactic potential of the Poznan University of Technology" - POKL.04.03.00-00-259/12, implemented within the Human Capital Operational Programme, co-financed by the European Union within the European Social Fund.

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(Received: 6. 10. 2015, revised: 3. 12. 2015)