NEW METHODS FOR MULTISOURCE UHF-ACOUSTIC PD LOCATION ON POWER TRANSFORMERS

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Abstract: Scope of this work is the development of an UHF-acoustic testing system based on a planar uniform linear array of ultrasonic transducers that provides the possibility to detect multiple PD sources in a transformer. In order to detect multiple sources, a location must be performed with each PD event, even if the signal is buried in noise. This is achieved by using advanced methods of signal processing presented in the paper. The use of newly designed statistical filters improves the detection of weak acoustic signals in noise corrupted environments, and makes detection possible even if the signal level is below the noise level. Statistical data evaluation methods allow reliable location results for variant measurements. The planar sensor array enables the user to locate PD in transformers with a single spot measurement. By using this method an estimation of a PD location is possible, even if signals can only be picked up in very few places around a transformer due to strong signal attenuation. Combined with UHF sensing, the developed system is capable of locating PD from a single measurement location only, improving convenience, reliability and accuracy of PD locations.

1 SENSOR ARRAY APPROACH

The location method is based on a combined ultrasonic and UHF measurement. A valve antenna[1] is placed inside the transformer tank through an oil valve. The UHF emissions of a PD event are used to trigger the measurement and to determine the temporal origin of the partial discharge. Alternatively a measurement according to IEC60270[2] can be used for triggering as well. Figure 1 displays the sensor arrangement.

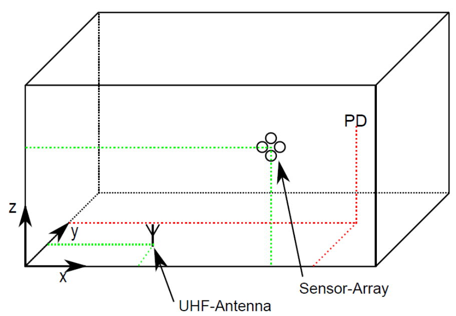

Figure 1: Sensor arrangement

An acoustic uniform linear sensor array consisting of two ultrasonic sensor pairs (four sensors or three with one shared) is mounted cross-shaped with a sensor spacing *d* on the surface of the tank, recording the acoustic emissions of partial discharges. A software algorithm calculates the acoustic wave's angle of arrival (AoA) to the sensor array as well as the distance of the PD to the sensor array.

With this sensor arrangement, in difference to traditional distributed sensor arrangements, the location of a PD can be calculated even if signals can only be picked up at limited or even a single location at the transformer tank.

1.1 Distance calculation

The distance d_{PD} of the PD source to the acoustic sensor array can easily be calculated using the time Δt that passed between the UHF (or IEC) trigger and the first detected acoustic wave at the sensor array multiplied with the sonic speed in oil v_{oil} as depicted in equation (1). The start time of an acoustic signal at the sensor array is determined by use of either the Hinkley criterion[3] with or without pre-processing using adaptive noise cancellation, or by use of matched filters[4].

$$d_{PD} = \Delta t \cdot v_{oil} \qquad (1)$$

1.2 Angle of arrival estimation

In order to assess the AoA of the acoustic waves to the sensor array the input signals of the array are processed. An inter sensor time delay calculation between adjacent sensors on the sensor axes by means of cross correlation is used to calculate the AoA.

1.1.1. Inter-sensor time delay calculation

The inter-sensor time delay of an input sequence of two adjacent sensors is calculated by the cross correlation of the two sequences. With the input sequences S_i and S_j to sensors *i* and *j* the cross correlation is calculated as shown in equation (2).

$$(S_i * S_j)[n] = \sum_{m=-\infty}^{\infty} S_i[m] \cdot S_j[n+m] \qquad (2)$$

The index n_{max} for which $(S_i * S_j)[n]$ reaches its maximum, the length (in samples) of one input sequence and the sampling frequency F_s are used to calculate the sequence delay t_{delay} between the sensors. This relation is shown in equations (3) and (4).

$$n_{\max} = \{ n \mid (S_i * S_j)[n] = \max \} \qquad (3)$$

$$t_{delay} = \frac{length(Sequence) - n_{\max}}{F_s} \qquad (4)$$

1.1.2. Angle Calculation

From the inter arrival time $t_{delay,i}$ of the signals at the sensors on a sensor axis *i* so called angle of arrival ambiguity cones can be derived. These cones are defined by angles $\Phi_{ULA,i}$ according to equation (5). The acoustic waves reaching the sensor have their origin on the surface of these cones.

$$\phi_{ULA,i} = \arcsin\left(\frac{t_{delay,i} \cdot v_{oil}}{d} \right) \qquad (5)$$

Figure 2 and Figure 3 show the determination of this angle and the resulting ambiguity cone.

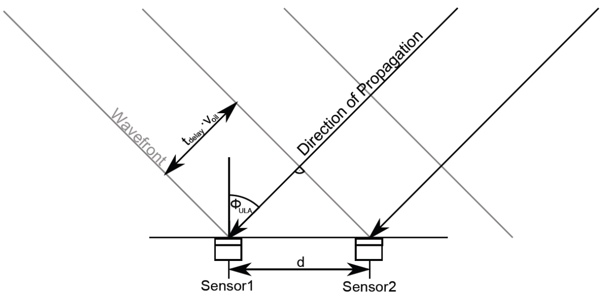

Figure 2: Inter arrival time and cone angles

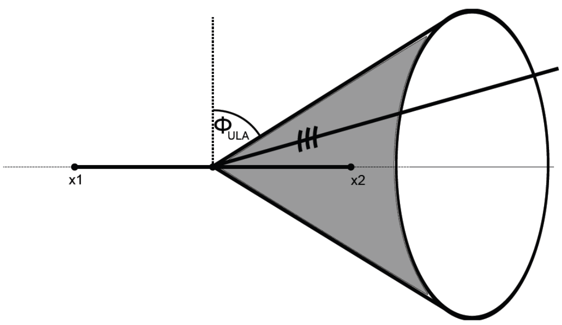

Figure 3: Ambiguity cone of one sensor pair

With two sensor axises, e.g. according to Figure 4, two cones can be determined. The intersection of these cones is a straight line connecting the PD source and the sensor array's location. Figure 5 shows the ambiguity cones calculated based on the inter arrival times at a sensor array. The line of intersection is marked green. In a transformer, the tank wall would be at *y=0* with the inside of the transformer at *y>0*.

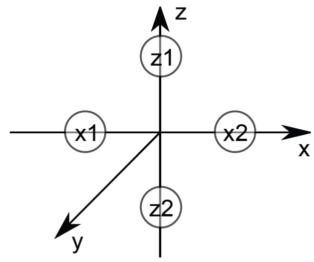

Figure 4: Example sensor arrangement

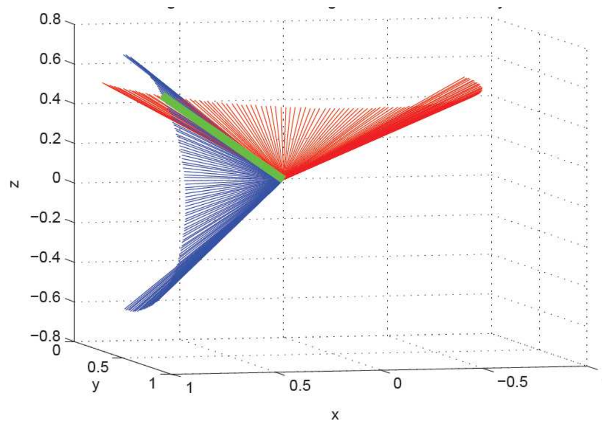

Figure 5: Intersection of ambiguity cones (green)

The direction of the interstection is defined as shown in equation (6).

$$\overline{direction} = \begin{bmatrix} x_{dicection} \\ y_{dicection} \\ z_{dicection} \end{bmatrix} \qquad (6)$$

1.3 Location of PD

Knowing the sensor position $\overline{Sensor}$, the direction of the ambiguity cone intersection $\overline{direction}$ and the distance between acoustic sensor array and PD source d_{PD}, the location $\overline{PD}$ of the PD can be calculated according to equations (7) and (8).

$$\overline{Sensor} = \begin{bmatrix} x_{sensor} \\ y_{sensor} \\ z_{sensor} \end{bmatrix} \qquad (7)$$

$$\overline{PD} = \overline{Sensor} + d_{PD} \cdot \overline{direction} \qquad (8)$$

2 ADVANCED METHODS OF SIGNAL PROCESSING

A limiting factor in acoustic PD location is noise. The determination of the parameters required for a location depend on the signal quality and in this sense mainly on the signal to noise ratio (*SNR*). For traditional methods noise is also preventing the possibility of detecting multiple PD sources, as explained in the subsequent sections.

2.1 Noise and arrival time determination

For a location of PD inside a transformer using acoustic sensors the arrival time of the acoustic signals at the sensors is important. For both, traditional distributed sensor arrays as well as for arrays presented in this paper, an accurate estimation of the arrival time is important for a location of PD.

However a commonly faced problem with acoustic PD measurements is the presence of noise. The arrival time determination of a PD signal superimposed with noise may not be accurate or not be possible, depending on the signal to noise ratio. This problem can be solved by means of averaging, using an UHF or IEC trigger to superimpose multiple measurements[3].

Averaging works, if only one PD source within the transformer is active. The presence of multiple sources would lead to a mixture of superimposed signals, where no arrival time determination is possible.

In order to locate multiple PD sources in a transformer, the signal's arrival times of each PD event need to be detected, even under noisy conditions, *without* averaging. Sections 2.3 and 2.4 introduce methods that allow doing so.

2.2 Noise and AoA estimation

As the noise is additive white Gaussian noise (*AWGN*)[3], it has little influence on the AoA estimation by means of cross-correlation, as white noise does not correlate and only non-random signals contribute to the cross-correlation result. Thus the inter arrival time determination is rather insensitive to AWGN, and an estimation is still possible even if the signal strength is much less than the noise level[4]. However a certain variance is added to the estimation. As shown in section 3 the application of statistical analysis methods allows to accurately locate PD if the required parameters are determined with variance.

2.3 Noise suppression using adaptive LMS-Filter

[5] introduced a method of noise suppression applied on ultrasonic material testing. The adaptive least mean squares filter shown in [5] can also be used to cancel AWGN from ultrasonic PD measurements. It allows the detection of the arrival time under noisy conditions within a single measurement, but deteriorates the signal shape and thus influences the AoA estimation negatively.

Figure 6 displays the structure of the filter according to [5]. The input sequence *s(n)* consists of the acoustical signal *x(n)* and the additive noise *r(n)*. The algorithm adjusts the filter coefficients so that the difference between the input signal and the adjacent sample of the output sequence *e(n)* of the filter becomes minimal. Due to the statistical nature of *x(n)* (natural) and *r(n)* (random), the output sequence of the filter becomes an estimation of *x(n).*

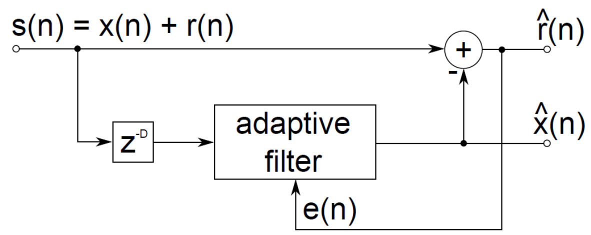

Figure 6: LMS filter structure

An example of a noise superimposed PD signal and its corresponding filter output is displayed in Figure 7. The noisy signal is blue, the filtered signal red and the original signal without noise is a dashed blue line. At the bottom the time scale is magnified to show the beginning of the signal.

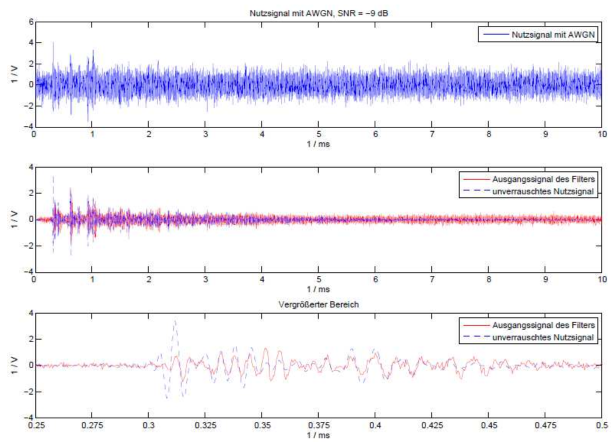

Figure 7: LMS filter signals

2.4 Arrival time estimation using matched filters

The arrival time estimation for acoustic PD signals can be performed using matched filters. A matched filter is used detect "reference sequences" within measured data. Figure 8 displays the structure of a matched filter. The impulse response of the matched filter is the time inverse of the reference sequence that the filter is searching for. If a part of the filtered signal sequence correlates with the reference sequence, the filter output indicates the presence of that sequence.

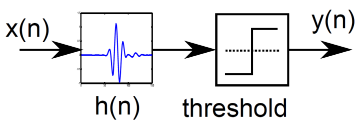

Figure 8: Matched filter structure

For a noisy PD measurement, the detection of a natural PD signal within the noise is desired. Thus a reference signal is chosen based on known signal properties of acoustic PD signals. It is known that the prevalent frequency of an acoustic PD signal is around 150kHz[3] which was also the resonance frequency of the sensors used in this test setup. Thus a reference sequence was modeled accordingly as depicted in Figure 9.

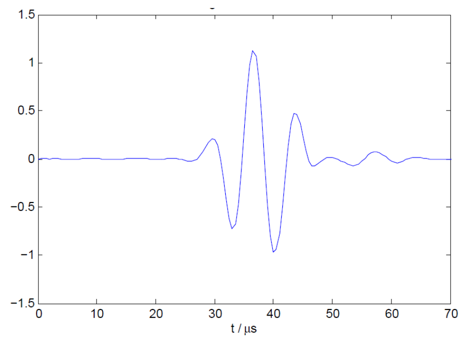

Figure 9: Matched filter reference sequence

Figure 10 shows a noise free sequence (upper part) and the corresponding matched filter output (lower part). The first peak is used to determine the arrival time.

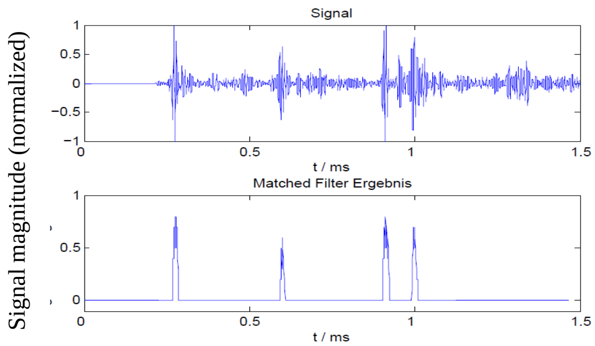

Figure 10: Matched filter result (no noise)

The same signal with a signal to noise ratio *SNR = -12dB* is shown in Figure 11. The filter detects the signal even though it is superimposed with strong noise.

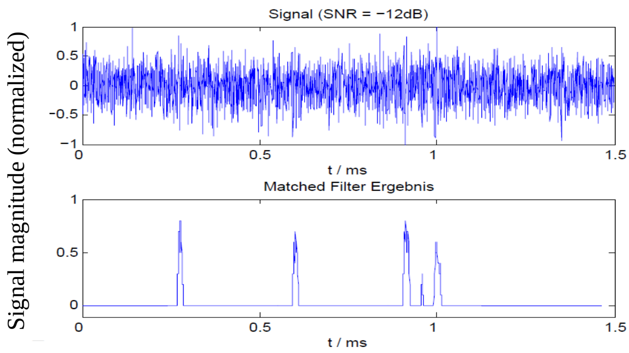

Figure 11: Matched filter result (SNR = -12dB)

Although strongly corrupted with noise, the application of matched filters for arrival time estimation of acoustic signals is still possible down to an SNR of -12dB[4].

3 STASTICAL LOCATION ANALYSIS

Arrival times of acoustic waves at sensors can be determined accurately even with strong noise corruption using filter methods as shown above. However the presence of noise adds a certain variance to the extracted parameters signal runtime and angle of arrival. Thus the location result, which is based on these parameters, becomes variant. In order to accurately derive location results, a statistical analysis of these results is performed in order to estimate the expectation value/values of the variant location distributions.

3.1 Clustering

The clustering method introduced by [4] uses a k-means clustering that sorts a series of location results into clusters. Results below a certain distance to adjacent results are grouped together. For measurements with multi variant locations a certain number of clusters are derived. The centre of gravity of measurements belonging to *one* cluster is the estimate location of a PD belonging to the variant location results of that cluster. The number of measurements belonging to a cluster in relation to the total number of measurements defines the probability of a PD to be related to the location (centre of gravity) of that cluster. Figure 12 displays an example of a variant measurement. Clusters are indicated by different colours. The more locations belong to a cluster, the higher the probability of a PD to be related to it.

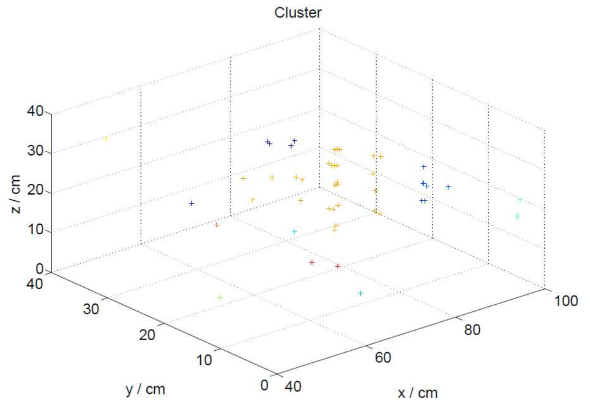

Figure 12: Clusters of a variant measurement

3.2 Kalman filtering of results

For monovariant location distributions, that means measurements with only one source, a Kalman Filter[6] can be used to estimate the actual location result, based on assumed variance information[4]. Kalman filters are used to observe systems, estimate the actual state of a system and predict future states of a system based on current and past observations as well as information about the process variance of the systems. In [4] such a filter is used to observe the cone angles and signal runtime of an array measurement. Given only a few measurements the Kalman filter is able to predict the actual location of a PD with a deviation of less than 15cm. However the Kalman filter cannot distinguish between two or more different PD sources, what makes it only applicable for one source. Figure 13 shows an example of a Kalman filtered measurement. The software displays a three dimensional representation of the measurement setup. The green cross is the sensor location on the tank wall (blue lines). The red dots are location results based on variant raw data, the blue dots are the Kalman filtered results. On the left hand side the determined values for the cone angles theta and phi (angle/° over measurements) and the distance d_{PD} (r/cm over measurements) is displayed. Again red values are variant data, blue values are Kalman estimations.

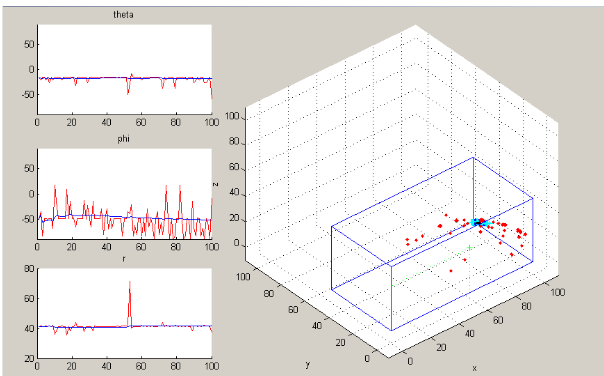

Figure 13: Ex. of a Kalman filtered measurement

4 CONCLUSION

Methods of noise cancellation and statistical data analysis presented in this paper introduce significant improvements for noise corrupted acoustic PD measurements and locations.

The location method based on a local sensor array allows to locate PD in transformers even if signals can only be picked up at limited areas, e.g. due to obstacles and barriers covering the transformer tank walls inside.

Its performance was tested both in laboratory and transformer test lab setups in 2009[7].

5 REFERENCES

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