Identification of Wavefronts in Partial Discharge Acoustic Signals using Discrete Wavelet Transform

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***Abstract* - This paper describes a method to discriminate the wavefront of the acoustic signal obtained from Partial Discharges. The technique used here takes advantage of the Wavelet Transform in order to extract, in a very precise way, the characteristics related to the desired wavefront. This information is used to locate the source of the Partial Discharge occurring in oil-insulated Power Transformers. The methodology to find the correct spot of the Partial Discharge uses Genetic Algorithm to solve a set of non-linear equations. Practical results are shown and the methodology is described in detail.**

I. Introduction

The health of large transformers is one of the biggest concerns in electric management system. A sudden fail can cause interrupts of high cost to the energy distributor and to the consumers. One of the most important sources of defects capable to produce catastrophic fail in large transformers is the partial discharge (PD). Partial discharge begins its activity almost inconspicuously and evolutes furtively until the disruption of the insulation and the consequent destruction of the equipment. So, an effective maintenance strategy is of utmost importance to guarantee the correct operation of these transformers.

Partial Discharge (PD) is a natural phenomenon that occurs in insulation systems under electric voltage and, as its evolution, tends to gradual deteriorate the insulation medium, diminishing its isolation capacity. It can be detected using many strategies, since electric detection at the transformers terminals to chemical analysis of the insulation material. One method that can be very useful, due this non-invasive characteristic, is the acoustic monitoring, because its capability to detect the defect in it's early stage and locate it. Localization of partial discharges is almost as important as the detection, because it allows the evaluation of the severity. However, there are difficulties in the process of localization by acoustic method that can produce misleading information. The method proposed in this work uses wavelet transform to process the acoustic signals obtained from the transformer and extract from them the information needed to locate the source of the PD in the transformer.

In previous work [1], a solution to the problem of the localization was presented using a Genetic Algorithm. However, for its correct operation, it is necessary to extract reliable information from the acoustic signal. Other work [2] suggests the use of the FFT for this purpose, but due to non-stationary nature of these signals, it becomes inadequate and difficult to repeat systematically. The information to be extracted is lies in the time and frequency of the acoustic signal. So, it is necessary to handle information in time and frequency domain simultaneously. The Wavelet Transform shows up as a good tool to deal with this kind of problem.

This paper describes a solution to extract information from acoustic signals caused by partial discharges, in order to locate its source in an oil-insulated transformer. The method uses the Discrete Wavelet Transform to deal with wave propagation problems in oil and at the metal wall, identifying the correct wavefront. Its contribution lies on the use of the wavelet transform to accomplish this task and on the identification of signal characteristics related to acoustic wave propagation in oil.

II. The Localization Problem

As explained in [1], the localization problem can be illustrated in Fig.1. Sensors are spread out all over the walls of the tank [1] and any point can be adopted as the origin of rectangular coordinates in three dimensions system.

A system of non-linear equations can be obtained considering each sensor as the center of a sphere, whose radius is the distance of this sensor to the source of acoustic emission. The value of the radius shall be given in terms of propagation speed of the acoustic wave in the transformer oil (v_S)and in terms of the time (Δt) which the acoustic wave takes to reach the point where the sensor is. The equation of the sphere is written in the following way:

$$(x-x_{S1})^2+(y-y_{S1})^2+(z-z_{S1})^2=r^2 \tag{1}$$

Where:

(x,y,z)	- variables.
(x_{S1},y_{S1},z_{S1})	- coordinator of the sensor $S1$.
r	- sphere radius.

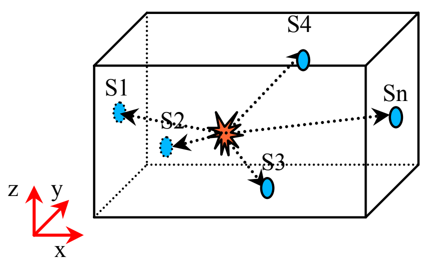

Fig. 1. Scheme for extracting the solution equations.

Writing (1) in terms of v_S and Δt:

$$(x-x_{S1})^2+(y-y_{S1})^2+(z-z_{S1})^2=(v_s\cdot\Delta t)^2 \qquad (2)$$

Where:

v_S - propagation velocity.

Δt - time propagation to reach sensor

The time intervals in which the acoustic wave takes to reach the sensors cannot be directly obtained. So, time differences between the first sensor reached by the acoustic emission and the other were recorded. Stated that, the unknown factors of the problem shall be: the time interval T between the occurrence of the PD and the detection of the acoustic wave by the nearest sensor; and the coordinates (x, y, z) of the position of the acoustic emission source. Therefore, a non-linear system with four equations is obtained:

$$(x-x_{S1})^2+(y-y_{S1})^2+(z-z_{S1})^2=(v_s\cdot T)^2 \qquad (3)$$

$$(x-x_{S2})^2+(y-y_{S2})^2+(z-z_{S2})^2=[v_s\cdot(T+\tau_2)]^2 \qquad (4)$$

$$(x-x_{S3})^2+(y-y_{S3})^2+(z-z_{S3})^2=[v_s\cdot(T+\tau_3)]^2 \qquad (5)$$

$$(x-x_{S4})^2+(y-y_{S4})^2+(z-z_{S4})^2=[v_s\cdot(T+\tau_4)]^2 \qquad (6)$$

where the τ_i are the time differences in relation to the first detection. The solution of this non-linear system results in the position of the partial discharge source.

However, it is not so easy to obtain the time differences τ_i. There are problems related to propagation modes of the acoustic waves produced by partial discharge in oil-insulated transformers. These waves are spherical and propagate in all directions. In the oil, they shall propagate in longitudinal mode until reach the transformer wall. At this point, there is a mode conversion producing a surface wave that is faster than longitudinal wave. If the sensor be at a position far from the partial discharge source, the first wavefront to reach it will not be the wave that travel in a straight path, but the wave that travel through the iron wall (Fig. 2). The result is a signal which has at least two wavefronts at the initial instants of waveform: one from the straight path wave and other from the circuitous path wave (the surface wave). Therefore, the problem is distinguishing one from the other and takes the time instant when the straight path wave reaches the sensor. With this time instants obtained from all the sensors, it can calculate the time differences τ_i.

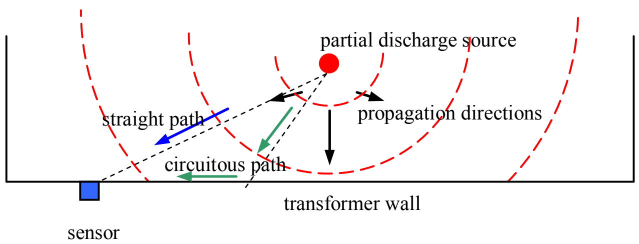

Fig 2. Propagation in different paths.

III. Distinguishing the Wavefronts With Discrete Wavelet Transform

A. Discrete Wavelet Transform and Multi-resolution

The multi-resolution is a concept related with the capacity to visualize a signal in different resolutions, i.e., to analyze a signal in different levels of details, being able to detach what it is more relevant in each level. The decomposition of a signal in different resolutions can be made with the Discrete Wavelet Transform. The importance of seeing the signal in different levels of details relies on the fact that the characteristics of a signal can be distributed in these levels. So, if the levels are separated, the characteristics also are.

1) Expanding a signal – Discrete Wavelet Transform is a kind of signal expansion. In this case, the expanding set is made up of wavelet functions and scaling functions. The expression is written like:

$$f(t)=\sum_{k=-\infty}^{\infty}c_{j_0,k}\cdot\varphi_{j_0,k}(t)+\sum_{j=j_0}^{\infty}\sum_{k=-\infty}^{\infty}d_{j,k}\cdot\psi_{j,k}(t) \qquad (7)$$

Where:

$c_{j0,k}$ - coefficients related with scaling functions, called *approximation coefficients*.

$d_{j,k}$ - coefficients related with wavelet functions, called *detail coefficients*.

$\varphi_{j0,k}$ - scaling functions expanding set.

$\psi_{j,k}$ - wavelet functions expanding set.

j - index related with scale.

k - index related with time.

The coefficients in the Discrete Wavelet Transform change related with two variables, i.e., these coefficients have two dimensions that cover the frequency content of signals and time content of signals. These coefficients can be organized in levels defined by the variable j, related with the concept of scale. The scale is a parameter related to the frequency and can be thought as the inverse of it. If the frequency increases, the scale decreases. The time information is preserved by the variation in k.

The Discrete Wavelet Transform is the process of calculate those coefficients. There are two ways to do this. One of them is through these expressions:

$$c_{j,k}=\langle f(t),\varphi_{j,k}(t)\rangle=\int f(t)\varphi_{j,k}(t)dt \qquad (8)$$

$$d_{j,k}=\langle f(t),\psi_{j,k}(t)\rangle=\int f(t)\psi_{j,k}(t)dt \qquad (9)$$

The other way is through an algorithm based on filter banks (Fig. 3), defined by:

$$c_{j,k}=\sum_m h(m-2k)c_{j+1,m} \qquad (10)$$

$$d_{j,k} = \sum_m h_1(m-2k)c_{j+1,m} \tag{11}$$

Where:

$h(\cdot)$ - FIR filter kernel related with scaling function.

$h_1(\cdot)$ - FIR filter kernel related with wavelet function.

The equations (10) and (11) define a filter process using a FIR structure, i.e., the discrete convolution. Associate with the filtering, there is a process of down sampling that reduces the dimension of data without loss of information. The reference [3] presents a very good explanation about these concepts.

2) Interpreting the coefficients – there is two types of coefficients: details and approximation. When the signal is decomposed with Discrete Wavelet Transform, it is broken in levels related each one to a frequency band. The number of levels is a parameter for this process.

The filter bank algorithm is recursive, as can be seen in Fig. 3. For the first level, it takes the signal and breaks it in two sets of coefficients: the approximation c_1 and the detail d_1. Then, it takes the approximation c_1 and repeats the process, breaking it in other two sets of coefficients: the approximation c_2 and the detail d_2. The algorithm repeats this process until the desired level is achieved. If the maximum level is n then the result shall be n levels of detail coefficients and one level of approximation coefficients.

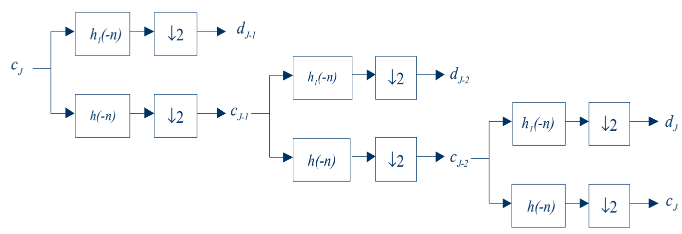

Fig. 3. Filter bank algorithm for the Discrete Wavelet Transform for three level decomposition.

The decomposition in each level is made by filtering the signal in a way that its limited frequency content is broken in two. One half, with lower frequencies, is the approximation, and the other, with higher frequencies, is the detail. This is illustrated in Fig. 4, for three levels of decomposition.

So, the Discrete Wavelet Transform of a signal results in a number of levels of detail coefficients and one level of approximation coefficients that retain the lower frequency content (Fig. 5). The frequency information is preserved at the levels of decomposition and the time information is preserved at the variation of the coefficients.

In Fig. 5, the signal was decomposed in two levels and the coefficients were used to reconstruct signals for each level. It is noticeable how the transients present in the signal can be easily revealed. This is possible because the concept of multi-resolution. The information was separated in several resolutions (levels), allowing the analyst to see details normally hidden when all of information is put together.

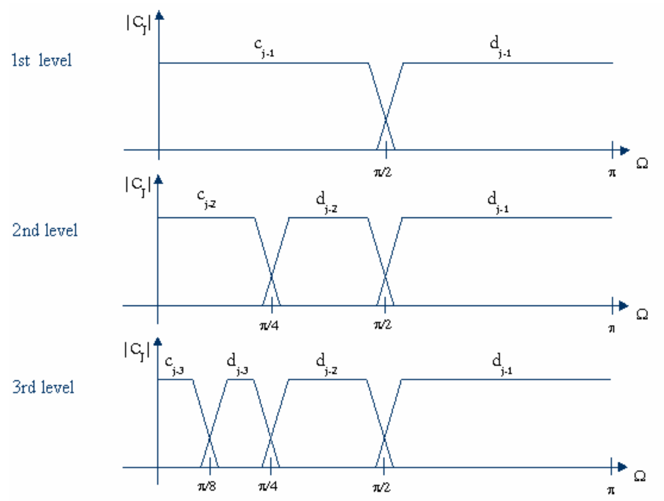

Fig. 4. Decomposition visualized at the frequency domain.

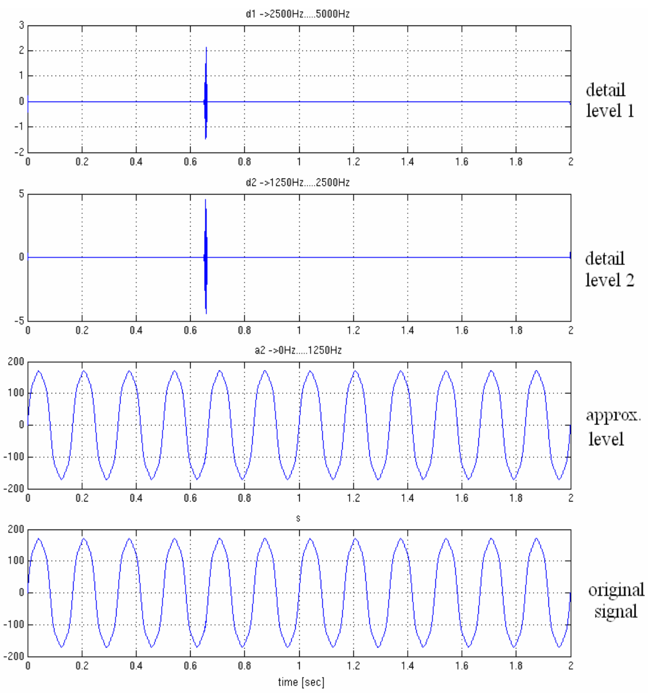

Fig. 5. Decomposition visualized in levels of reconstructed coefficients.

In this work, the information in coefficient levels is used to extract the instant when the acoustic wave traveling over the straight path reaches the sensor.

B. Distinguishing the Wavefronts

The sensor that picks up the acoustic emission signals can be reached by several wavefronts. Each one has a particular spectral characteristic. These wavefronts reach the sensor in different time instants causing small transients in the signal that are not visually detected. So, the multi-resolution ability of the Discrete Wavelet Transform can be very useful in the detection of those transients and their time instants.

To distinguish the wavefronts, the first step is taking the Discrete Wavelet Transform of the signal. The second step is to look at the level that contains the frequency components related to the wavefront whose time instant is wanted. If the selected level contain only the components of the searched wavefront, then must exist a coefficient that indicates the initial time instant of that wavefront. The index of this coefficient matches the time instant, but some adjustment is necessary due the down sampling used in the algorithm of the Discrete Wavelet Transform. The adjustment depends on the level of decomposition and can be written as:

$$i_S = i_C \cdot 2^{level} \tag{12}$$

Where:

i_S - index of the sample.
i_C - index of the coefficient.
level - level of decomposition.

There is an error introduced by this adjustment that becomes as large as the level increases:

$$e_{is\max} = 2^{level} - 1 \tag{13}$$

Where:

e_{ismax} - maximum error in the sample index.
level - level of decomposition.

The method described above was used to extract the time instant, when the wave traveling on the straight path reaches the sensors. Then, the time differences were calculated and the non-linear system of the localization problem is solved.

IV. Experimental Results

A. Equipments

The experiments were driven in a tank made with iron plates of thickness 2mm. The dimensions of the tank are 0.30m x 0.30m x 0.60m. The tank was filled with transformer oil. The sensors used were of broadband type, model S9208 made by the Physical Acoustic Corporation - PAC. They were fixed at the tank wall through magnetic straps and was used an ultrasonic gel as medium coupling between the sensor and the iron plate, according to the PAC recomendations.

The acoustic emission signal, from the sensors, was amplified in 40dB and acquired in a *National Instruments* PXI-6133 acquisition system. This equipment has 8 channels, 14bits of resolution and 2.5MSamples/second of sampling rate per channel (simultaneous). The programs Labview and Matlab were used to process and analyze the data.

B. Wave Characteristics

Initially, the frequency characteristics of straight path wave were unknown. So, one do not know what level (or levels) of wavelet decomposition contain the information of initial time instant of that wave.

The objective of this experience is to find a level, in Discrete Wavelet decomposition, where the initial instant of the straight path wave is easily detect. To solve this problems a special setup will be implemented, in order to separate and identify those kinds of characteristics, which are related with some level of wavelet decomposition.

The setup is illustrated in Fig. 6. Sensors S1 and S2 are positioned in such a way that their angles with the normal are below the critical angle, which is 13.6°. The reason for this is asseverate that sensors S1 and S2 will be reached firstly by straight path waves. Sensors S3 and S4 are placed in positions were the first wavefront to reach them had traveled by circuitous path (wall).

In this experiment, several signals were acquired to confirm the results. Here, it will be shown just one essay for demonstration, although a lot of them was necessary to discover the correct level. Each discharge event leads to an acquisition of four acoustic emission signals. One example of these signals is showed in Fig. 7. The exact instant where the discharge occurs and the sound velocity in oil are also measured.

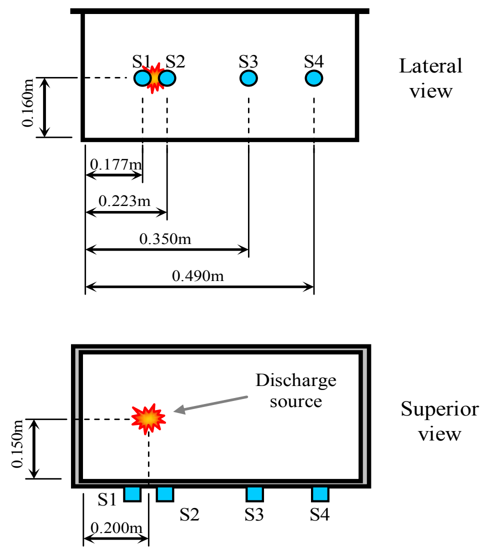

Fig. 6 Setup for characterization of acoustic wave.

Looking at the graphic in Fig. 7, one can see the two types of wavefronts in the acoustic signal. This kind of a signal must be detected by sensors S3 and S4. The objective of this experience is to characterize a level where only the wavefront of straight path wave appears, even in signals like the Fig. 7.

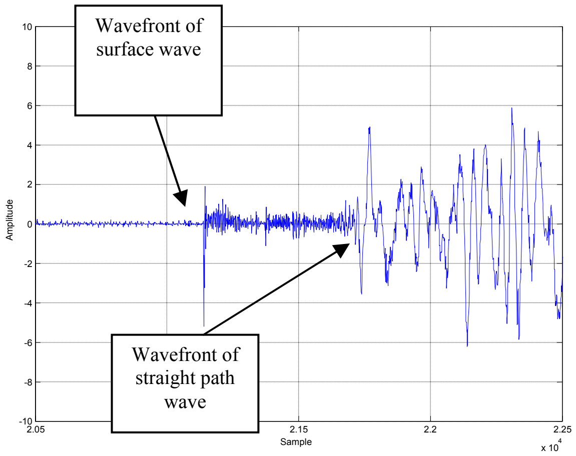

Fig. 7 Region of initial wavefronts of the acoustic emission.

Knowing the distances between the discharge source and the sensors, and the sound velocity in oil, it is possible to calculate the wavefronts sample index for the straight path wave. Using the Discrete Wavelet Transform, one can search in each level of decomposition a coefficient that matches the transient corresponding to the calculated initial instant of the straight path wave. If this coefficient is easily detected in some level, then one can use it as an indicator of such a wave.

In order to illustrate this experience, the Table I shows the calculated initial sample of the straight path wave and the Table II shows five levels of Discrete Wavelet decomposition (with Haar wavelet) with corresponding coefficients and relative samples of the wavefront most easily detected. The relative samples were calculated using Eq. (13).

TABLE I
CALCULATED INITIAL SAMPLE INDEX FOR THE STRAIGHT WAVE PATH

Sensor S1	Sensor S2	Sensor S3	Sensor S4
27697	27697	27806	28013

TABLE II
COEFFICIENT INDEXES AND RELATIVE SAMPLE INDEXES OF WAVEFRONTS INDICATED BY FIVE LEVELS OF DETAILS OF WAVELET DECOMPOSITION

Level	Indexes	Sensor S1	Sensor S2	Sensor S3	Sensor S4
1	Coefficient	13846	13850	13878	13963
	Relat. Sample	27692	27700	27756	27926
2	Coefficient	6923	6925	6946	6980
	Relat. Sample	27692	27700	27784	27920
3	Coefficient	3461	3462	3476	3495
	Relat. Sample	27688	27696	27808	27960
4	Coefficient	1731	1731	1738	1751
	Relat. Sample	27696	27696	27808	28016
5	Coefficient	865	866	869	875
	Relat. Sample	27680	27712	27808	28000

Comparing Table I and relative samples in Table II, one can search a level that approximately matches these two informations. After several essays, the level 4 was found as a good indicator of straight path wave. A lot of experiences were made and the results confirm the methodology. The next step is to apply this method in the PD localization problem.

C. Partial Discharge Source Localization

There are two distinct parts in the localization algorithm: detection of the straight path wave and solution of the non-linear system described in section II. With the straight path wave detection, explained above, the time differences τ_i can be calculated. A solution for the non-linear system for the localization problem can be obtained using either an iterative or an optimization method. In this work, a Genetic Algorithm was used.

As a demonstration, four essays were made: two position configuration for the sensors and, for each one, two different positions of PD source. These positions were registered to compare with the results provided by the algorithm. The system coordinates origin was chosen to be one of the tank corners. The results are presented in table III.

V. CONCLUSIONS

The method described here show the effectiveness of acoustic method for detect and locate PD in oil-insulated transformers. The analysis of the acoustic emission signal through the Discrete Wavelet Transform reveals the useful characteristic of the straight path wave, allowing its identification among other wavefronts. So, the initial instant of that wave was detected, then providing information to localize PD source.

The frequency band associated with level 4 level of acoustic emission signal decomposition, at a sample frequency of 2.5MHz, is 78.125kHz to 156.25kHz. This can be thought as the frequency characteristic of the straight path wave. However, there are not evidences that the level 4 decomposition, at 2.5MHz sample frequency, will be the best indicator for the straight path wave in all conditions of experiments, like oil type, wall thickness and material, among others. So, it is not recommended to take these frequency characteristics as the ultimate one.

A solution for the problem of distinguishing acoustic waves traveling in straight path was presented without using Fourier Transform, which is inappropriate for non-stationary signals like acoustic emissions.

A future work must improve this algorithm to handle with multi-material obstacles inside the tank. These obstacles should simulate the influence of core, insulation and winding in the acoustic emission.

TABLE III
RESULTS OF THE TEST WITH THE LOCALIZATION ALGORITHM

Essay	Sensor positions [m]				Discharge source position (x; y; z) [m]	Discharge source position provided by the algorithm (x; y; z) [m]
	S1 (x; y; z)	S2 (x; y; z)	S3 (x; y; z)	S4 (x; y; z)		
1	(0,300; 0,120; 0,000)	(0,000; 0,050; 0,110)	(0,600; 0,150; 0,150)	(0,350; 0,140; 0,300)	(0,240; 0,160; 0,100)	(0,242; 0,157; 0,094)
2	(0,300; 0,120; 0,000)	(0,000; 0,050; 0,110)	(0,600; 0,150; 0,150)	(0,350; 0,140; 0,300)	(0,110; 0,160; 0,150)	(0,110; 0,163; 0,146)
3	(0,500; 0,150; 0,000)	(0,090; 0,100; 0,000)	(0,600; 0,150; 0,150)	(0,130; 0,080; 0,300)	(0,425; 0,160; 0,180)	(0,434; 0,161; 0,198)
4	(0,500; 0,150; 0,000)	(0,090; 0,100; 0,000)	(0,600; 0,150; 0,150)	(0,130; 0,080; 0,300)	(0,050; 0,160; 0,050)	(0,052; 0,144; 0,049)

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