CONTRIBUTION OF THE TIME-FREQUENCY AND TIME-SCALE TRANSFORMS TO THE PARTIAL DISCHARGES ANALYSIS

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ABSTRACT

One of the problems of the Partial Discharges (PD) measurement is the discrimination of the signal versus the noise. A lot of techniques like frequency filtering already exist. This paper presents time-frequency techniques to extract the PD signal from the noise. Two transforms are presented : Short Time Fourier Transform and Wigner Distribution. The mathematical tools for the implementation of the STFT are given. An example of extraction of a PD signal from numeric noise is given and it result discussed. The characteristics of the PD signal permit to use another type of transforms : the wavelets. The mathematical tool is presented and discussed, especially for the extraction of PD signal from a PWM supply.

INTRODUCTION

We have to work in time and frequency domains to analyze the Partial Discharges. Statistical tools and Phase Resolved Partial Discharges (PRPD) Pattern are currently used to analyze the PD [1]. The importance of frequency data for the PD analysis [2] and the problems of noise in the PD measurement are both principal reasons to work in the frequency domain. The classical transforms like the fast Fourier transform (FFT) enable us to go from time domain to frequency domain and inversely, but, don't enable to work on both domains. During the 20th century, Time-Frequency Transforms were developed. The first one is the Short Time Fourier Transforms (STFT). This transform is frequently used, especially for the voice treatment. It is easy to implement and gives good results. We present also the Wigner distribution and its advantages and disadvantages. The latest tool is Wavelet or time-scale-transform. It appeared about 20 years ago.

The first part of this paper presents the time frequency transforms and gives an example to illustrate it. The second part gives examples of single PD treatment and gives results of PD signal denoising. The last part of this paper presents the problems related to the measurement and discusses the mathematical tools to solve them.

THEORY AND IMPLEMENTATION OF THE TIME-FREQUENCY TRANSFORMS

The FFT enables to analyze the signal in the time domain or in the frequency domain. The transforms that we present in this chapter enable to work in both domains. To do that we work on the on the complex form of the signal. This form is

$$\tilde{s}(t) = s(t) + jH[s(t)] \qquad (1)$$

where H[s(t)] is the Hilbert transform of the real signal.

We present the Short Time Fourier Transform (STFT) and the Wigner Distribution (WD). They are presented with test signals to evaluate them and to make a choice for the PD analysis. The signals chosen to do this test are sum of sinusoids and linear chirp :

$$x(t) = \sin(2\pi f_1 t) + \sin(2\pi f_2 t) \qquad (2)$$

where f1=200 Hz and f2=400 Hz

$$y(t) = \sin(2\pi ft) \qquad (3)$$

where f ranges from 50 Hz to 350 Hz

$$z(t) = x(t) + y(t) \qquad (4)$$

SHORT TIME FOURIER TRANSFORM

To study the properties of a signal at time t, one emphasizes the signal at that time and suppresses the signal at other times [3]. This is achieved by multiplying the signal by a window function, centered at t, to produce the modified signal.

$$s_t(\tau) = s(\tau).h(\tau - t) \qquad (5)$$

The modified signal is a function of two times, the fixed time we are interested in, t, and the running time, τ. The window function is chosen to leave the signal more or less unaltered around time t. every point outside this window is put at zero to suppress the signal for time distant from the time of interest.
The term "window" comes from the idea that we are seeking to look at only a small piece of the signal as when we look out of a real window and see only a relatively small portion of the scenery. in this case we want to see only a small portion.
Since the modified signal emphasizes the signal around time t, the Fourier transform will reflect the distribution of the frequency around that time,

$$S_t(\omega) = \frac{1}{\sqrt{2\pi}} \int e^{-jw\tau}.s_t(\tau).d\tau \qquad (6)$$

where ω is the pulsation of the signal, $\omega=2\pi f$ (f is the frequency in Hz). Following the formula (1),

$$S_t(\omega) = \frac{1}{\sqrt{2\pi}} \int e^{-jw\tau}.s(\tau).h(\tau - t).d\tau \qquad (7)$$

the energy density spectrum at time t is therefore

$$P_{SP}(t,w) = \left|S_t(w)\right|^2 = \left|\frac{1}{\sqrt{2\pi}} \int e^{-jw\tau}.s(\tau).h(\tau - t).d\tau\right|^2 \qquad (8)$$

for each different time we get a different spectrum and the totality of these spectra is the time-frequency distribution, P_{SP}. It goes under many names, depending on the field. In this paper, we use the most common phraseology, "spectrogram". The figures 1b, 2b and 3b give examples of test signal defined as above.
Since we are interested in analyzing the signal around the time t, we have chosen a narrow window peaked around t. Hence the modified signal is short and its fourier transform, equation (3), is called Short-time Fourier transform. When we want to estimate time properties for a given frequency we do not take short times but long ones. In this case the windows function on the frequency is short to respect the uncertainty principle of Heisenberg. We can define a Short Frequency Fourier Transform by

$$s_{\omega}(t) = \frac{1}{\sqrt{2\pi}} \int e^{jwt}.S(\omega').H(\omega'-\omega).d\omega' \tag{9}$$

If we relate the window function in the time h(t) and the windows function in the frequency H(ω) by

$$H(\omega) = \frac{1}{\sqrt{2\pi}} \int h(t).e^{-j\omega t} dt \tag{10}$$

then

$$S_t(\omega) = e^{-j\omega t}.s_{\omega}(t) \tag{11}$$

The short time Fourier transform is the same as the Short Frequency Fourier Transform except for the phase factor $e^{-j\omega t}$. Since the distribution is absolutly square, the phase factor does not enter into and either the short-time Fourier transform or the Short Frequency Fourier Transform can be used to define the distribution,

$$P(t,w) = |S_t(\omega)|^2 = |s_{\omega}(\omega)|^2 \tag{12}$$

this shows that the spectrogram can be used to study the behavior of time properties at a particular frequency. This is done by choosing a narrow window in frequency or likewise by taking a broad window in time. Therefore we can make a narrowband or a wideband spectrogram by choosing size of the window in the time domain.

WIGNER DISTRIBUTION

The Wigner distribution is the prototype of distributions that are qualitatively different from the spectrogram. Wigners original motivation for introducing it was to be able to calculate the quantum correction to the second virial coefficient of a gas. The Wigner distribution was introduced into signal analysis by Ville. The Wigner transform in terms of the signal is

$$W(t,\omega) = \frac{1}{2\pi} \int s^*(t-\frac{\tau}{2}).s(t-\frac{\tau}{2}).e^{-j\omega\tau}.d\tau \tag{13}$$

The Wigner distribution is said to be bilinear in the signal because the signal enters twice in its calculation. It is to be noticed that to determine the properties of the Wigner distribution at a time t we mentally fold the left part of the signal over the right one to see if there is any overlap.

As we can see on the signal y(t) defined by the equation 3 (figure 2a) the Wigner distribution (figure 2c) has a better contrast than the Short Time Fourier Transform (figure 2b). it is interesting for the strongly non stationary signals. The figure 1 presents the sum of sinusoids x(t) defined by the equation 2. The STFT gives only both frequencies but with broad band. The WD gives the both frequencies with a narrow band but we can see a lot of interference terms especially in the band of 300 Hz. These terms of interference are mathematical artifacts generated by the distribution.

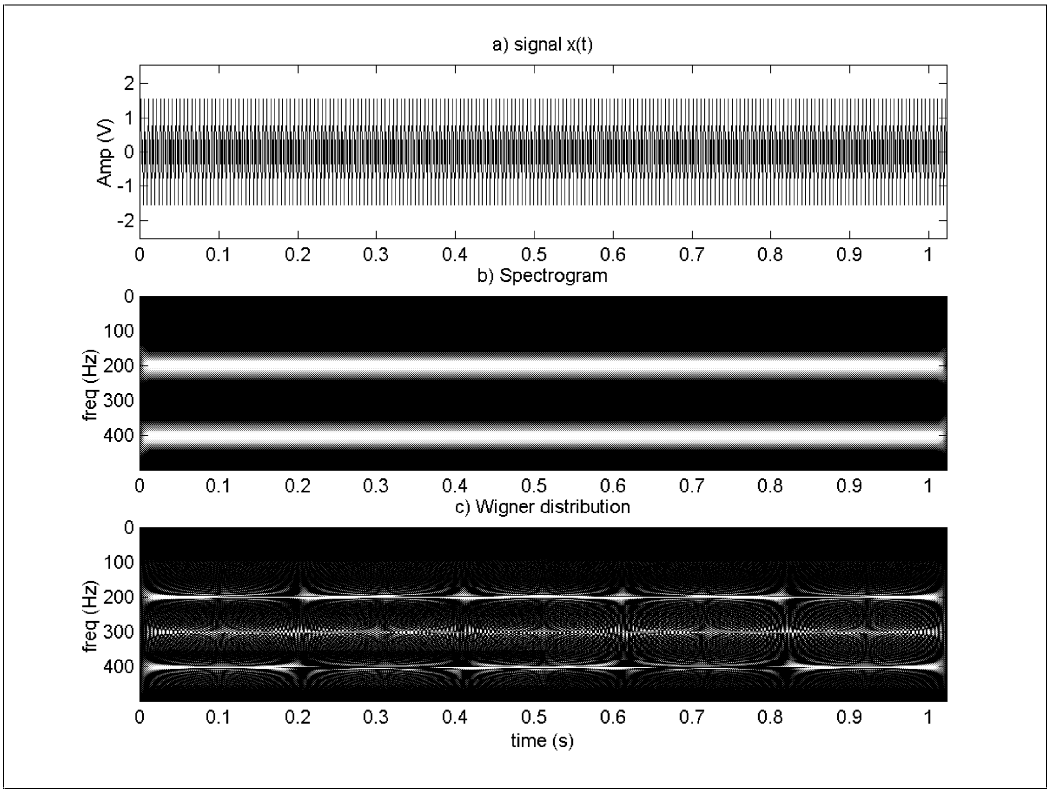

Figure 1 : Spectrogram and Wigner distribution of the signal x(t)

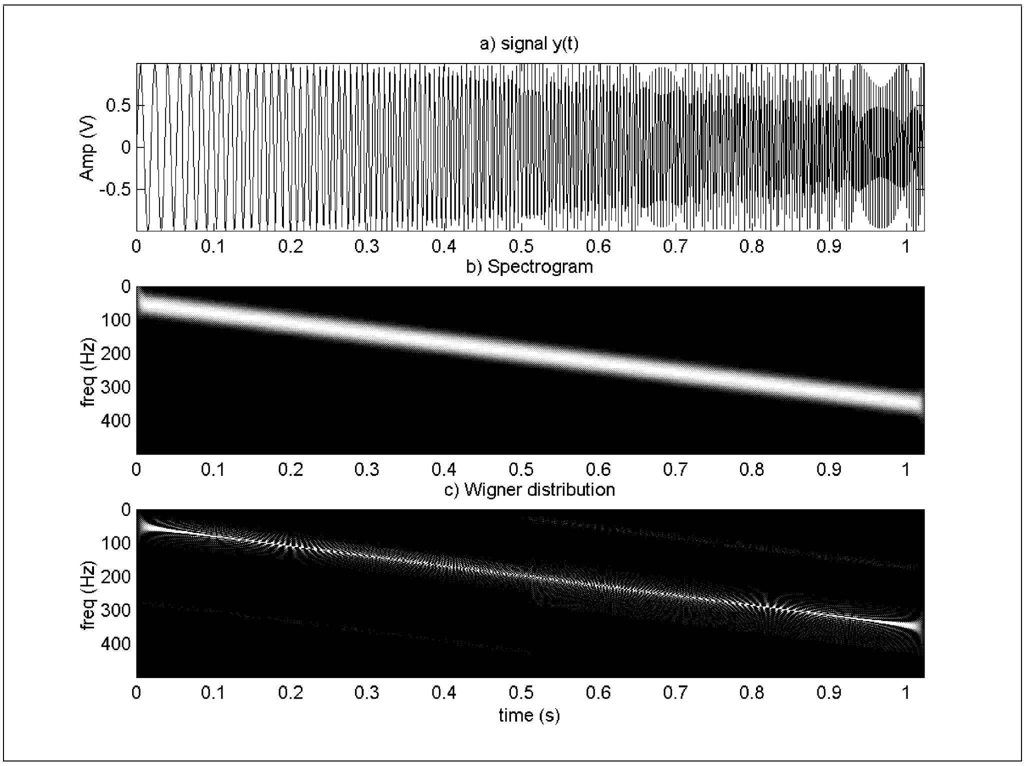

Figure 2 : Spectrogram and Wigner distribution of the signal y(t)

The sum of both signals is defined as the equation (4) of the signal z(t). Its Wigner distribution is

$$W_z(t,\omega) = W_x(t,\omega) + W_y(t,\omega) + W_{xy}(t,\omega) + W_{yx}(t,\omega) \quad (14)$$

The cross Wigner distribution is complex. However, $W_{xy} = W_{yx}^*$ and, therefore, $W_{xy}(t,\omega) + W_{yx}(t,\omega)$ is real. Hence

$$W_z(t,\omega) = W_x(t,\omega) + W_y(t,\omega) + 2.\mathrm{Re}\{W_{xy}(t,\omega)\} \quad (15)$$

We see that the WD of a sum of two signal is not the sum of the WD of each signal but has the additional term2.Re{Wxy(t,ω)}. It is our term of interference. On the one hand the signal z(t) (equation (4) figure 3a) is easily readable with the spectrogram (figure 3b). On the other hand the artifacts generated by the terms of interference blur the information on figure 3b. the work inside the classes of Cohen and the treatment of the ambiguity function enable to reduce this problem. But it is not the objective of this paper.

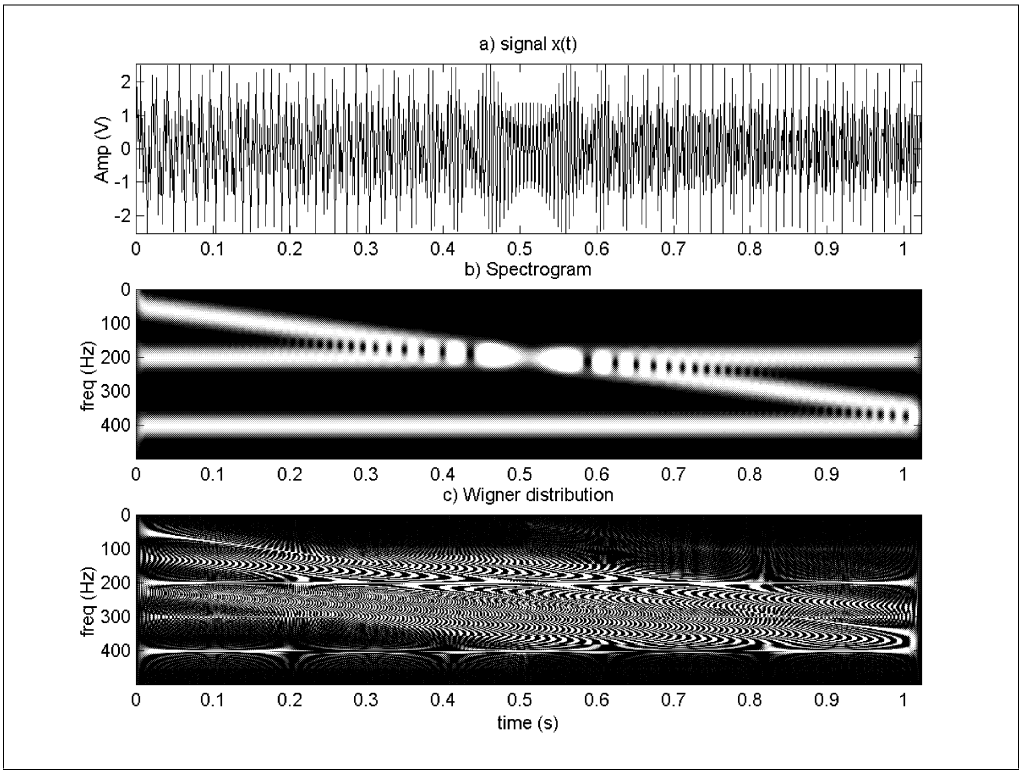

Figure 3 : Spectrogram and Wigner distribution of the signal z(t)

SINGLE PD TREATMENT IN THE TIME FREQUENCY SPACE

The first application that we propose is the study of one single PD in the time-frequency space. This PD was measured by a capacitive probe on one sample composed of a polyester-mica tape. The details of the sample are not so important in this paper. The amplitude of the noise around the PD is relatively small (figure 4). The PD is measured with a frequency of 250 MS/s on 256 samples. The bandwidth of the PD is around 70 MHz. The STFT (figure 5) presents a readability until 60 MHz for two reasons, first one is the quality of the graphic, second one is the choice of the window. The WD is more efficient (figure 6). The frequency and the position on the time are more readable. On the figure 6 we can see the interference terms near the self terms. The sum of the interference terms is null. The noise is not readable on the figure 5 and 6 because its amplitude is so less important than the PD amplitude. The figure 7 presents the STFT of the PD signal in logarithm scale. In this representation, we can see the spectrogram of the noise.

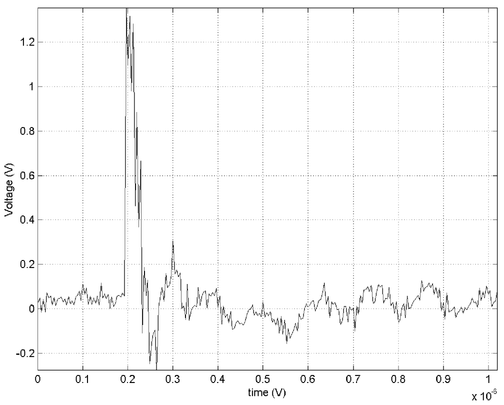

Figure 4 : single PD signal

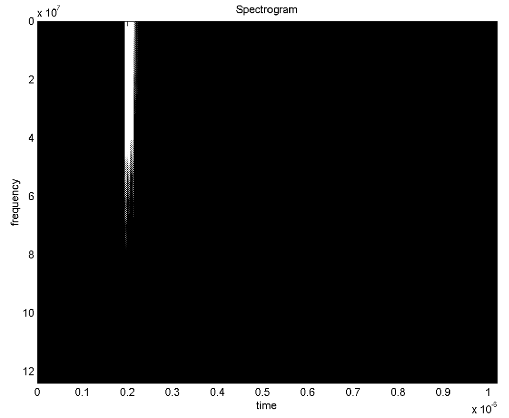

Figure 5 : STFT of the single PD signal

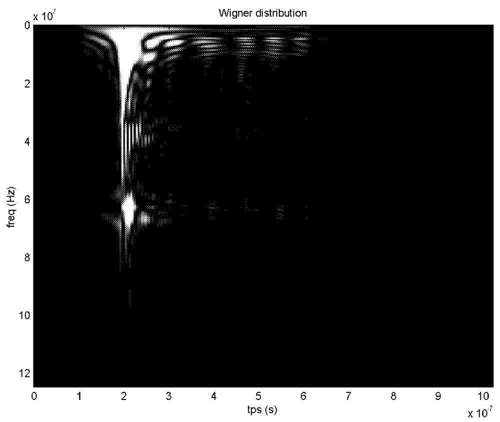

Figure 6 : WD of the single PD signal

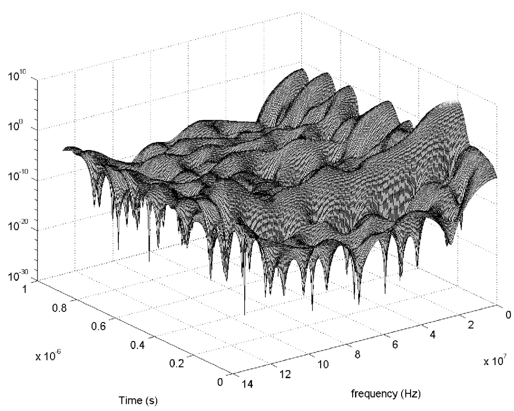

Figure 7 : log scale of the STFT of the single PD

TIME-FREQUENCY PD ANALYSIS ON ONE SUPPLY PERIOD

One classical process to analyze the partial discharge is the examination of the PD on one supply period. The figure 8 presents the PD measurement on the same sample as the single PD measurement. This measurement is made at 34 MS/s. Thanks to the single PD analysis, we know that this frequency band is not adequate and the PD signal has a lot of chance to look like Dirac signal.

To test the efficiency of the time-frequency transform, we add numeric noise at the measured signal (figure 9). The added signal is composed by white noise, sinusoidal noise and choke noise. From this new signal we must analyze and denoise it with mathematical tools in order to obtain as well as possible the original signal (figure 10).

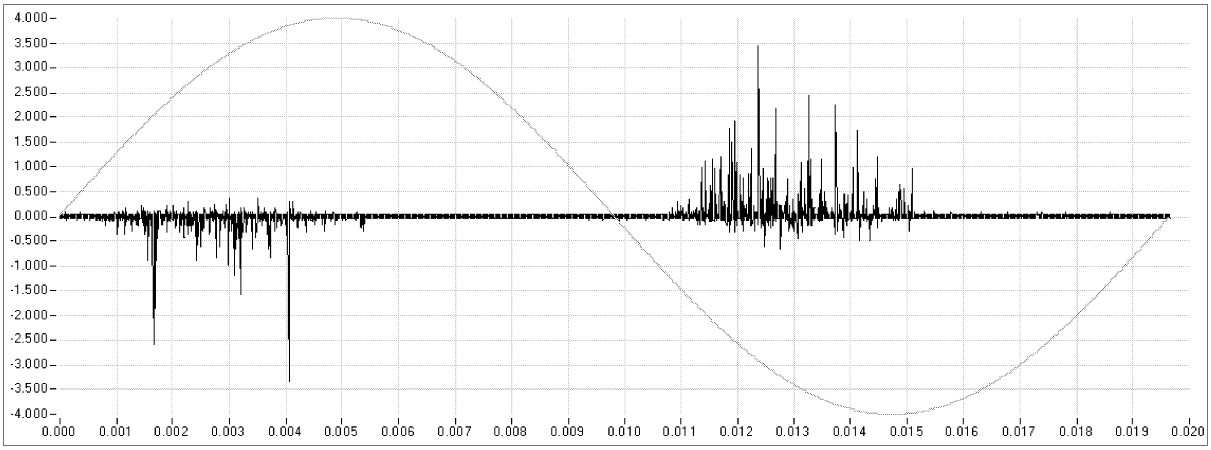

Figure 8 : PD signal measured

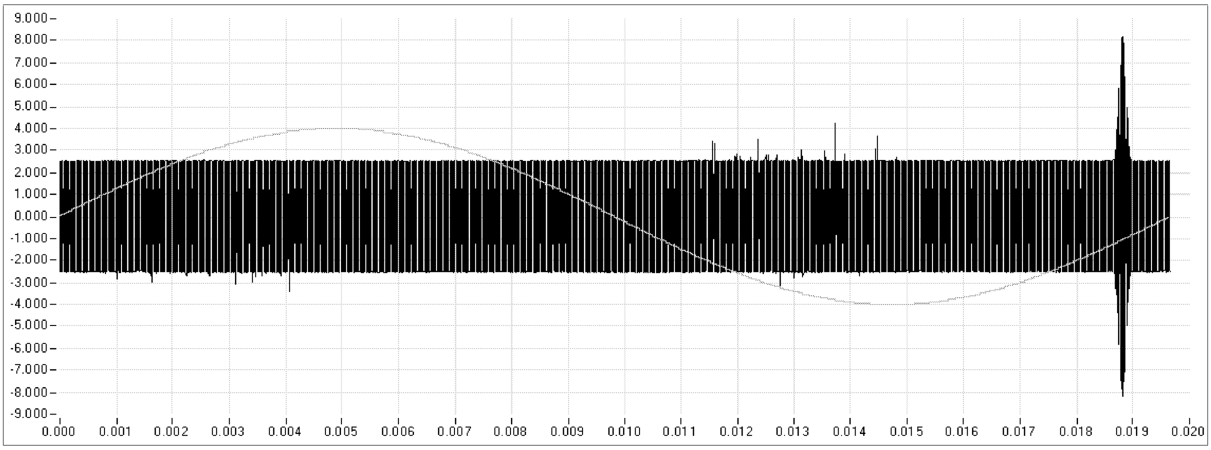

Figure 9 : Noised signal

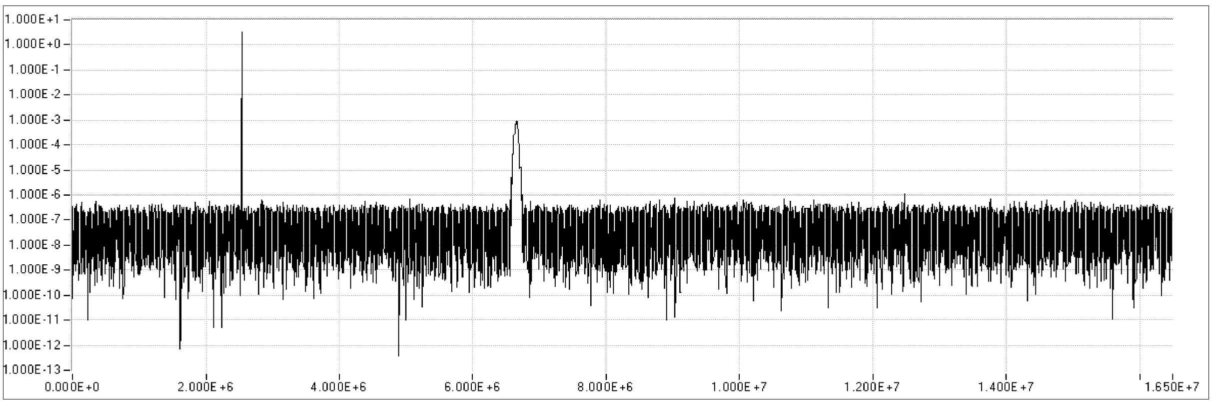

Figure 10 : FFT of the noised signal

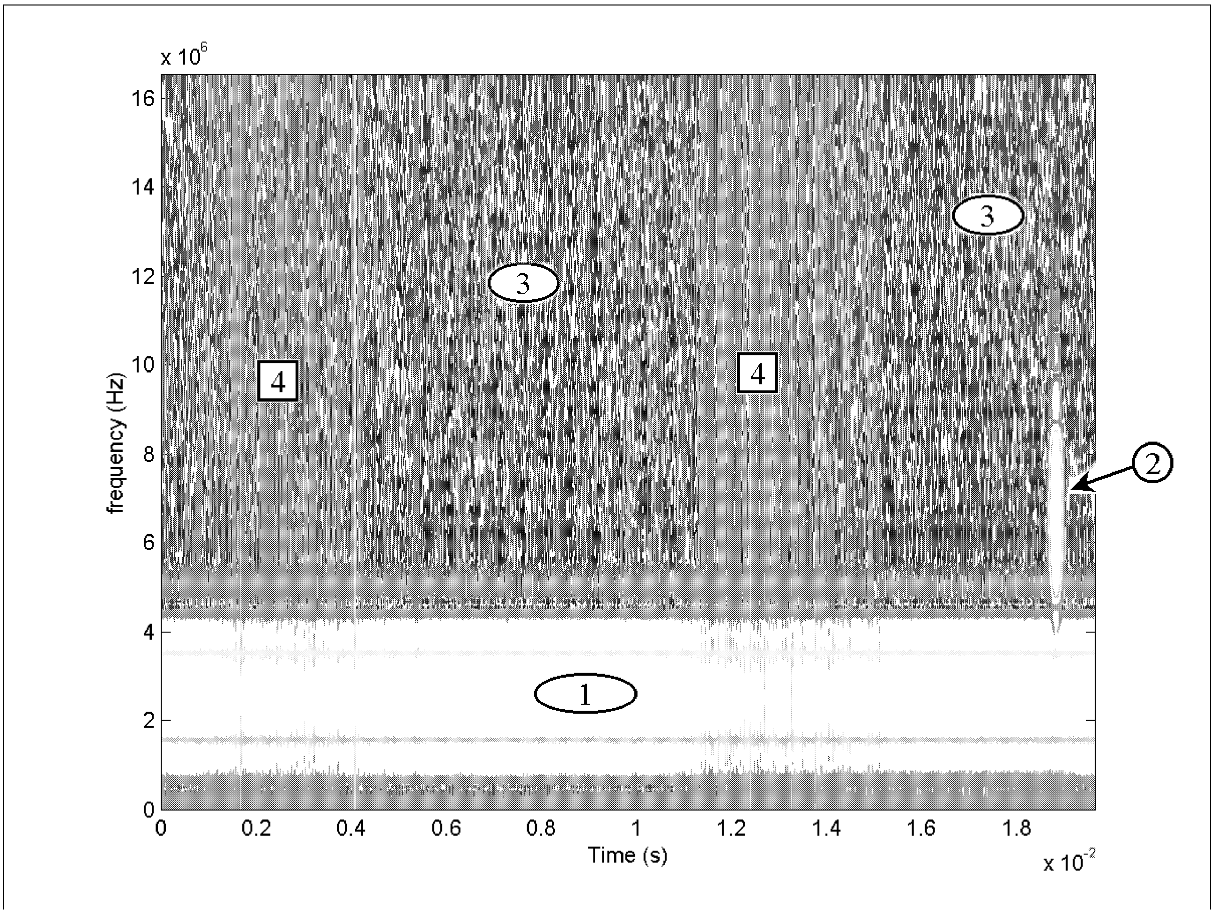

Figure 11 : Spectrogram of the noised signal

On the spectrogram (Figure 11), we can see different zones (even if it is difficult to read a spectrogram in black and white). The bands in white on the zone N° 1 are periodic components of the signal they are present at every point of the time. We can see them in the FFT (Figure 10). We can eliminate them by filtering. The zone N° 2 is the chock. We can also see it in the spectrum but the best solution to eliminate it is in the time domain. It is the same for the white noise (zone N° 3). The zone N° 4 contains white noise and PD signal.

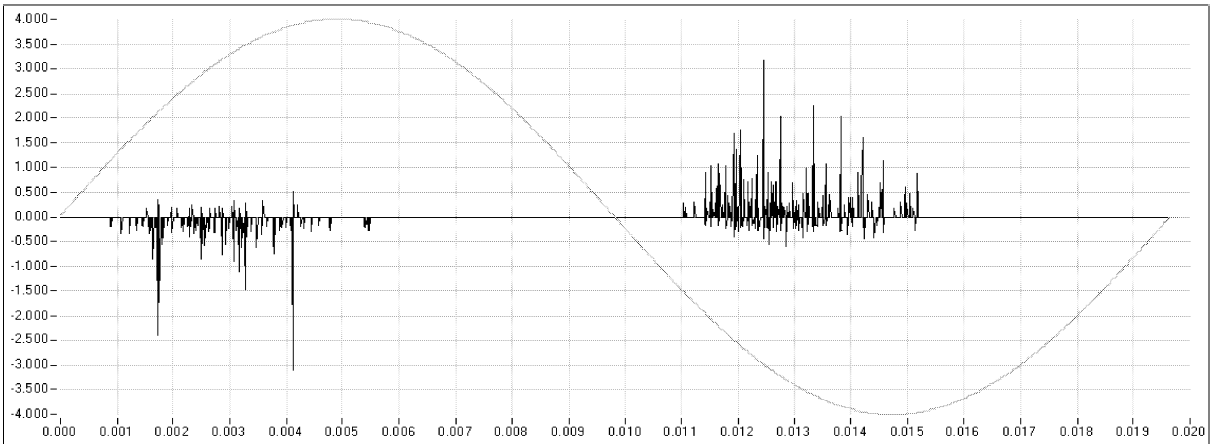

Figure 12 : Denoised signal

The figure 12 presents the result of the denoising. This result is obtained from recursive calculations in time domain and frequency domain. The denoised signal obtained can be used to do statistical treatment like PRPD pattern [1]. Of course, we loose one part of the information. But, in this case, we loose less information by numerical treatment than by the frequency band of the acquisition card.

The time-frequency distribution enables to make an analyze to determine the best tools to extract the signal from the noise. After this analysis, we can implement the tools used for the extraction on the machine to make an on line treatment. However the time-frequency transform are difficult to implement on line because the time of treatment can be too long.

PROBLEMS WITH CONVERTERS AND WAVELET

The main problem with the converters is the dV/dt. If we use capacitive probe, we have a problem of courant (i = C.dV/dt) and the bridge connection is very difficult. One way to solve this problem is to use inductive probes but the problems of attenuation or saturation are complex. The second way is, of course, to use signal processing to extract the PD signal. The figure 13 presents one waveform of a two levels converter. As we see, the classical tools like PRPD parttern are not adapted.

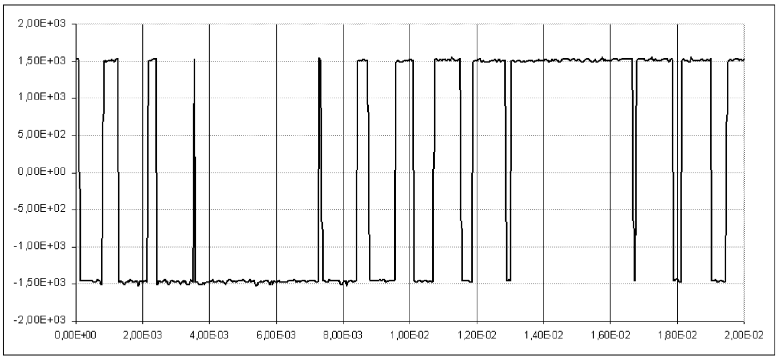

Figure 13 : One period 50 Hz from a 2 levels converter

The time-scale transforms wavelet transforms [4] seems to be a good tool to work on this problem for signal processing [5] and, perhaps, for the classification [6]. The general equation of the Wavelet transform is

$$X(a,b) = \frac{1}{\sqrt{a}} \int_{-\infty}^{+\infty} x(t).\psi\left(\frac{t-b}{a}\right).dt \qquad (16)$$

where Ψ is the mother wavelet, a the scale factor and b the translation factor. In fact the coefficient X(a,b) is the scalar product of the signal with the wavelet function more or less dilated and translated in the time axis. There are various wavelet fonctions : Morlet, Debauchie, Haar, etc. One difference between Time-Frequency transform and Time-scale transform is the distribution of the frequency. For the Time-Frequency Δf= Constant, for the time-Scale transform $\Delta f/f$= constant.

Presently we are working on the PD detection on converter supply and we develop the wavelet transforms.

CONCLUSION

The examination of the PD signal in the time-frequency space is helpful to discriminate the PD signal versus the noise. This technique enable to have a good idea of the PD environment. Therefore it should be interesting to prepare the instrumentation for the on line PD measurement.

The time-frequency treatment enables to fix a lot of problems of PD acquisition and extraction. However it don't seem the best way for the classification and the diagnostic. To do that, the wavelet-transforms seem more indicated [6].

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