Maurizio CACIOTTA[1], Sabino GIARNETTI[1], Fabio LECCESE[1], Zbigniew LEONOWICZ[2]

University Roma Tre (1), Wroclaw University of Technology (2)

Wavelets an Hilbert Transform for detection of short disturbances in electrical power networks

Abstract. *In electrical energy power network, disturbances can cause problems in electronic devices therefore their monitoring is fundamental to properly design the protection and compensation devices. In this paper we address the problem of disturbances' detection by using two different signal processing methods: Wavelets and Hilbert Transform (HT). Methods were tested under different conditions of noise and harmonic distortion (THD) showing the Hilbert Transform can be used as a valid approach for this type of phenomena.*

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Keywords: Power Quality, Wavelets, Hilbert Transform, voltage dips, transients.

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Introduction

Electric power quality has become an important area of interest in power systems, studied from a wide number of points of view: technical and scientific summarized in [1,2,3], in the field of economy, of social sciences and legal aspects of power quality [4,5,6,7,8] with emerging perspective of the Perceived Power Quality [7]. For this purpose there are many of electric parameters that help to describe the phenomena as a whole are reported in relevant standards. In this context, we consider disturbances as the temporary deviation of the steady state waveform caused by faults of brief duration or by sudden changes in the power system [2]. The disturbances considered by the International Electrotechnical Commission include voltage dips, brief interruptions, voltage increases, and impulsive and oscillatory transients [2, 3, 8]. The first ones are defined by norms as a sudden reduction (between 10% and 90%) of the nominal voltage, at a given point of electrical system, and lasting from half of the fundamental period to several seconds. The dips with durations of less than half a cycle are regarded as transients. The main characteristics of voltage dips are magnitude and duration, which correspond to the remaining voltage during the fault and the required time to clear the fault respectively. A voltage dip may be caused by switching operations associated with temporary disconnection of supply, the flow of heavy current associated with the start of large motor loads or the flow of fault currents or short circuits and earth faults. These last ones can be symmetrical (three phase) or non symmetrical (single-phase to ground, double-phase or double-phase-to-ground). The magnitude of a voltage dip at Point of Common Coupling (PCC) depends on the type of fault, the distance to the fault and the fault impedance [8]. Most of the voltage dips are the result of momentary distribution faults. The dip event lasts generally less than 200 milliseconds with magnitude less than 50% of nominal voltage [8]. The effects can be extremely annoying as extinction of discharge lamps, incorrect operation of devices; speed variations or stopping of motors; tripping of contactors; computer system crash or commutation failure in line commutated inverters.

The brief interruptions can be considered as voltage sags with 100% of amplitude. The cause may be a blown fuse or breaker opening and the effect can be an expensive shutdown. For instance, supply interruptions lasting up to few seconds may cost a lot in case of interruption of service or stoppage of machines in a production plant. Brief voltage increases (swells) are brief increases in r.m.s. voltage that sometimes accompany voltage sags. They appear on the unfaulted phases of a three phases of a three-phase circuit that has developed single-phase short circuit. Swells can upset electric controls and electric motor drives, particularly common adjustable-speed drives, which can trip because of their built-in protective circuitry. Swells may also stress computer components and shorten their life.

Voltage disturbances shorter than sags or swells are classified as transients and are caused by sudden changes in the power system [8]. According to their duration, transient overvoltages can be divided into switching surge (duration in the range of millisecond), and impulse spike (duration in the range of microseconds). Surges are high-energy pulses arising from power system switching disturbances, either directly or as a result of resonating circuits associated with switching devices. Protection against surges and impulses is normally achieved by surge-diverters and arc-gaps at high voltages and avalanche diodes at low voltages.

In this article we focus the attention on disturbances which will gain more importance in the future because of the increase of electronic devices that can be particularly sensible to this kind of problems if not adequately protected. In fact there are two important aspects that should be taken into account:

- The disturbance detection algorithm should be able to detect them as soon as possible, regardless of the nature of the voltage disturbance.
- At the same time, the disturbance estimation algorithm should have a good selective accuracy.

In all cases, in power quality, is necessary to detect not only the beginning and end of a voltage sag but also to determine the sag depth and the associated phase angle jump.

The aim of future research, where the presented research results will be applied, is distributed instrumentation system based on personal computers, which are common in office or domestic environment. This allows to conjugate the high PC calculation capability with the possibility to send data via internet to a central server; moreover, the use of the existing hardware infrastructure makes the instrumentation affordable. Nowadays, the absence of continuative measurements carried out on the electrical network makes it impossible to evaluate the quality of electrical energy forcing the companies to adopt alternative solutions to compensate the possible lack of quality. Big companies, in order to assure the continuity of the service, adopt complex and redundant electric supplies, as it is valid for small customers that, for example, use UPS for their PCs. This is reflected into additional costs which are almost exclusively covered by the customers.

Low Voltage (LV) customers are particularly affected by this problem: both because their small commercial dimensions lower their capability to negotiate the price of electric energy and its quality, above all because they cannot fully realize their needs and expectations towards this good.

The instruments are conceived to be affordable with the idea to be easily placed in the final customers' site. In consequence, employed algorithms must be simple and robust. Hilbert Transform demands little computation power and is assumed to perform well in presence of expected disturbances. The performance of HT is compared to a special class of wavelet transform, known to be best suited to analyse short, impulse signals [9].

This paper is organized as follows: We present applied wavelet algorithm for disturbances detection. In next section, a description of Hilbert Transform methodology is proposed as an effective way for disturbance detection. Then, the algorithms are compared under different real test conditions where the influence of point on wave, noise level and THD variation is discussed. Finally, main conclusions are presented.

Wavelets application for voltage dip detection

Wavelets provides a fast and effective way of analysing non-stationary voltage and current waveforms and can be applied for precise computation of the beginning of a disturbing event, as shown in this paper. The ability of wavelets to focus on short time intervals for high-frequency components and long intervals for low-frequency components improves the analysis of signals with localised impulses and oscillations, particularly in the presence of a fundamental and low-order harmonic [6,9].

The continuous *Wavelet Transform* (CWT) of a signal $x(t)$ is defined as:

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

where $\psi(t)$ is the mother wavelet, and other wavelets

(2) $$\psi_{a,b}(t) = \left(\frac{1}{\sqrt{a}}\right)\psi\left(\frac{t-b}{a}\right)dt$$

are its dilated and translated versions, where a and b are the dilation parameter and translation parameter respectively, $a \in R^{+} - \{0\},\ b \in R$ [9, 11].

The discrete WT (DWT), instead of CWT, is used in practice [11]. Calculations are made for chosen subset of scales and positions. This scheme is conducted by using filters and computing the so called *approximations and details.* The *approximations (A)* are the high-scale, low frequency components of the signal. The *details (D)* are the low-scale, high-frequency components. The DWT coefficients are computed using the equation

(3) $$X_{a,b} = X_{j,k} = \sum_{n \in Z} x[n] g_{j,k}[n]$$

where $a = 2^{j}$, $b = k2^{j}$, $j \in N$, $k \in Z$. The wavelet filter *g* plays the role of ψ [9].

The decomposition (filtering) process can be iterated, so that one signal is broken down into many lower resolution components. This is called the *wavelet decomposition tree*. For detection of transients a multi-resolution analysis tree based on wavelets has been applied. Every one of wavelet transform subbands is reconstructed separately from each other, so as to get $k+1$ separated components of a signal $x[n]$. The choice of mother wavelet is different for each problem at hand and can have a significant effect on the results obtained. Orthogonal wavelets ensure that the signal can be reconstructed from its transform coefficients .

As wavelet the *symlets* function was used. The symlets are nearly symmetrical wavelets proposed by Daubechies as modifications to the "db" family - orthogonal wavelets characterized by a maximal number of vanishing moments for some given support (Fig. 1). Transient's detection was realized through tracking values of details (D) representing higher frequencies in the signal. High value indicated the presence of a transient. In contrary to other presented method this approach did not use the amplitude parameter of the main component which was prone to noise and other high frequency disturbances.

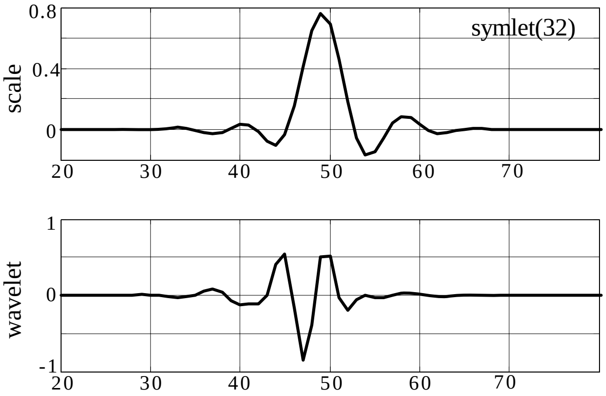

Fig.1. Scale and wavelet *symlets* function for 32 coefficients

The Figure 2 shows the behaviour of the wavelet decomposition of the sinusoidal waveform distorted by one voltage dip. The decomposition was made using the Daubechies 6 wavelet at the D2 level.

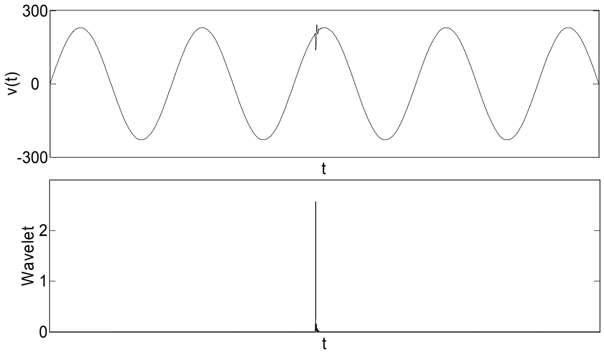

Fig. 2. Wavelet decomposition (lower plot) of the sinusoidal waveform (upper plot) distorted by one transient impulse.

Hilbert Transform theory and implementation

The Hilbert Transform of a real-valued time domain signal $x(t)$ is another real-valued time domain signal, denoted by $\tilde{x}(t)$, such that $z(t) = x(t) + j\tilde{x}(t)$ is an analytic signal [10, 12]. From $z(t)$ one can define a magnitude function $A(t)$ and a phase function $\theta(t)$, where the first describes the envelope of the original function $x(t)$ versus time, and $\theta(t)$ describes its instantaneous phase. The Hilbert transform of a real-valued function $x(t)$ of infinite time is a real-valued function $\tilde{x}(t)$ defined by:

(4) $$\tilde{x}(t)=H[x(t)]=\int_{-\infty}^{\infty}\frac{x(u)}{\pi(t-u)}du$$

The analytic signal $z(t)$ associated with $x(t)$ can be rewritten also as:

(5) $$z(t)=A(t)e^{j\theta(t)}$$

and

(6) $$\theta(t)=\tan^{-1}\left[\frac{\tilde{x}(t)}{x(t)}\right]=2\pi f_0 t$$

so the “instantaneous frequency” is given by:

(7) $$f_0=\left(\frac{1}{2\pi}\right)\tan^{-1}\left[\frac{\tilde{x}(t)}{x(t)}\right]=2\pi f_0 t$$

The Fig. 5 shows the signal envelope of the sinusoidal waveform distorted by one short transient computed using the Hilbert Transform decomposition.

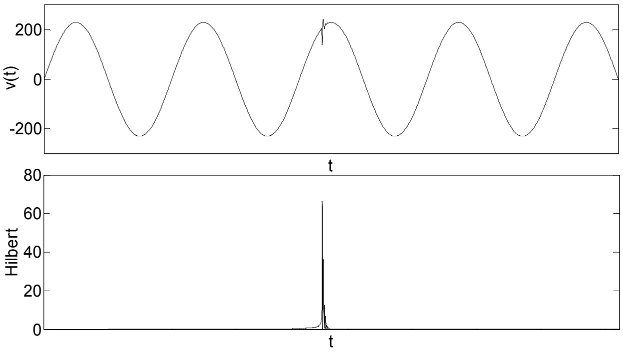

Fig. 5. Hilbert Transform decomposition (lower plot) of the sinusoidal waveform (upper plot) distorted by one short transient.

Experimental test cases

For experimental testing the performance of the algorithms, we used a synthesized signal realized by MATLAB able to generate short voltage transients of different magnitudes.

For evaluating the performance of the two methods, test signals has been used with varying Total Harmonic Distortion (THD) and Signal-to-Noise Ratio (SNR). The THD used are 5.7%, 11.2% and 22.4%. These values were obtained using for each of the first 24 harmonics the half of the norm limits, the norm limits, and the double of norm limits.

For each of the three distorted signals, three signals with varying SNR: 100dB, 80dB and 60dB has been created. The added noise is white Gaussian. For signals with higher harmonic contents this method did not perform well. Assumingly, higher order frequency components present in the signal deteriorated the detection ability (Fig.6).

Two wavelets with significantly different lengths have been used for test signal decomposition; *Symlet* (length of the filter 32 samples) and *Daub 6* (length of the filter 6 samples).

To the nine test signals 100 short transients have been added, one for each period in random position. In tables 1 and 2 are reported the results of detected disturbances using HT and Wavelets for transients of the amplitude of 35V and 100V, respectively 15% and 43% of nominal voltage.

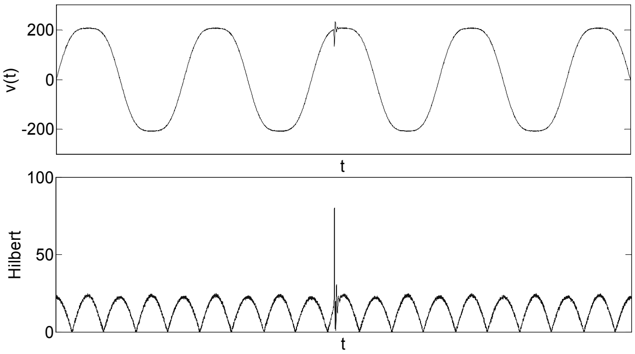

Fig.6. Hilbert Transform decomposition (lower plot) of the sinusoidal waveform with harmonics (upper plot) distorted by one impulse.

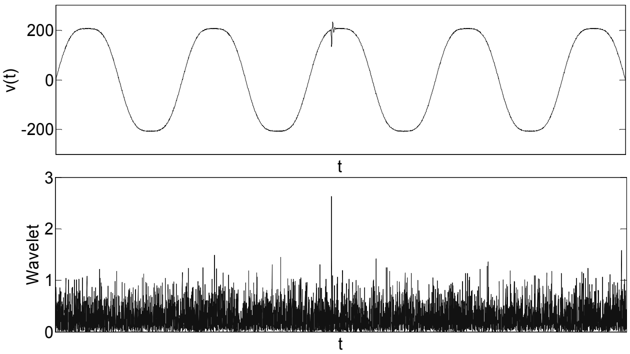

Fig.7. Wavelet decomposition (lower plot) of the sinusoidal waveform with harmonics (upper plot) distorted by one impulse.

Table 1. Detection rate of 35V impulse distortion by Wavelet and Hilbert transform

SNR / THD	100 dB		80 dB		60 dB	
	HT	Wavelet	HT	Wavelet	HT	Wavelet
5.7 %	100 %	100 %	94 %	45 %	48 %	12 %
11.2%	44 %	100 %	28 %	45%	17 %	17 %
22.4%	5 %	100 %	4 %	33%	3 %	14 %

Table 2. Detection rate of 100V impulse distortion by Wavelet and Hilbert transform

SNR / THD	100 dB		80 dB		60 dB	
	HT	Wavelet	HT	Wavelet	HT	Wavelet
5.7 %	100 %	100 %	100 %	100 %	100 %	70 %
11.2%	100 %	100 %	100 %	100%	98 %	67 %
22.4%	63 %	100 %	56 %	100%	51 %	62 %

The results show that the result obtained by Hilbert Transform processing are more sensible to harmonics distortion than to noise. On the other hand, the wavelet approach ensures good performance in presence of high THD, but the percentage of detected impulse disturbances is strongly reduced by even moderate noise levels.

Next Figures show the results of analysis of the sinusoidal signal distorted by noise and harmonics. The Figure 8 shows results for the signal distorted by harmonic (up to 24th harmonic) where the Total Harmonic Distortion (THD) is about 50%.

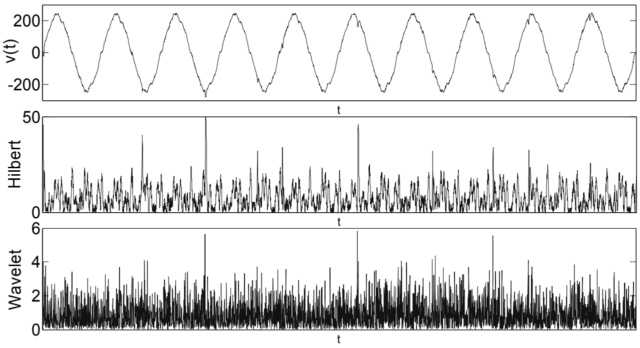

Fig.8. Signal with low harmonic and impulse distortion (upper plot) and high noise level; decomposition using the Hilbert Transform (middle) and wavelets (lower plot).

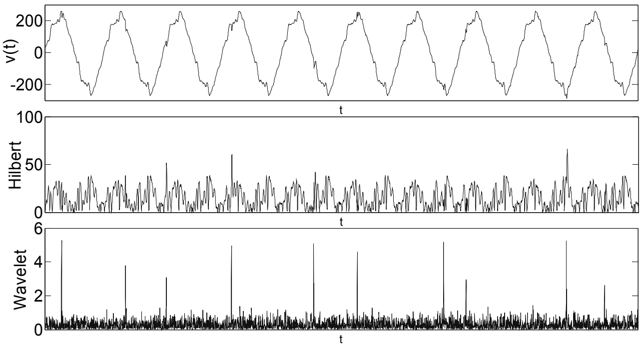

Fig.9. Signal with high harmonic and impulse distortion (upper plot) and low noise level; decomposition using the Hilbert Transform (middle) and wavelets (lower plot).

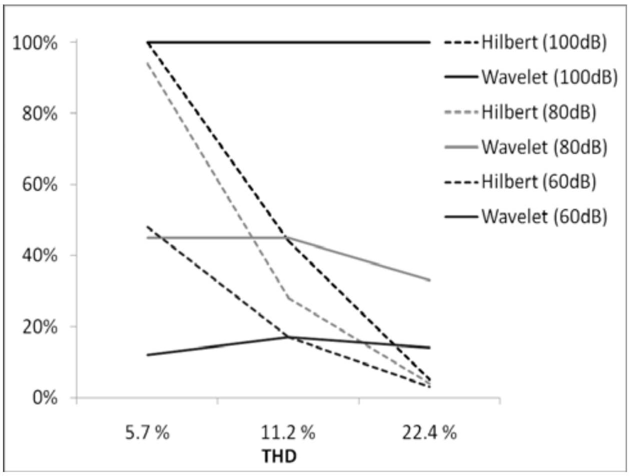

Fig. 10 .Comparison between Hilbert Transform (dashed line) and Wavelet (solid line) for three different SNR values and THD values.

The Fig. 10 summarizes the performance of Hilbert and Wavelet Transform in the presence of different THDs and different SNRs. It appears that the Hilbert Transform approach is better than Wavelet in case of lower SNR.

The real signal (Fig. 11) recorded in an industrial environment was used for testing of the HT processing. Short impulse transient is clearly detected using the HT method, Fig 12.

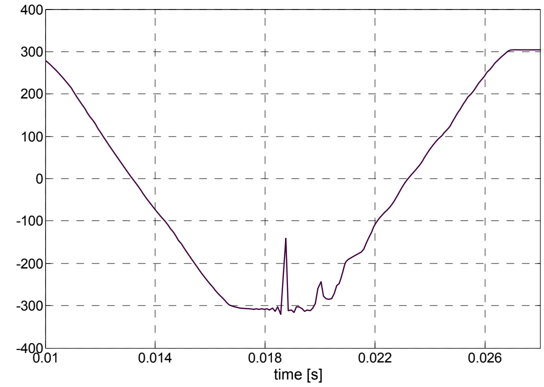

Fig.11. Recorded voltage waveform with a short transient.

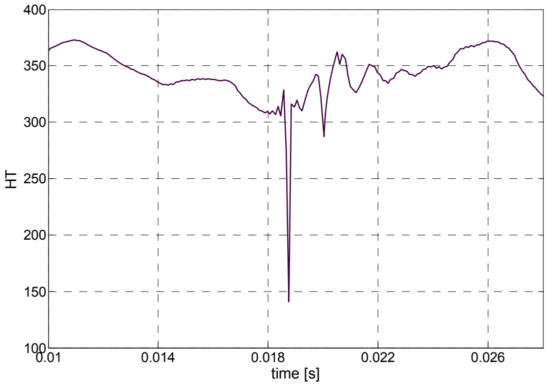

Fig.12. Hilbert Transform processed signal.

Conclusions

This paper has investigated two detection algorithms for short impulse disturbances, such as Wavelet transform and Hilbert transform. The performance of the amplitude estimation method is compared in relation to the detection accuracy for each detection algorithm to show the presence of an impulse disturbance. Both methods prove to be a good evaluation tool this type of disturbances but Hilbert transform is less prone to noise and harmonic disturbances with high frequency components.

Results from the study indicate that Wavelet Transform is able to detect impulse disturbances better in the presence of higher harmonic disturbances but it is more affected by noise while Hilbert Transform based algorithms are more immune to noise but relatively more affected by high level of signal shape distortion.

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***Authors**: prof. Maurizio Caciotta, Sabino Giarnetti, dr Fabio Leccese, Universita Roma Tre, Dipartimento di Ingegneria Elettronica, Via della Vasca Navale, 84, 00146 Roma, Italy, E-mail: caciotta@uniroma3.it, sgiarnetti@uniroma3.it, leccese@uniroma3.it, dr inż. Zbigniew Leonowicz, Instytut Podstaw Elektrotechniki i Elektrotechnologii, Politechnika Wrocławska, Wyb. Wyspiańskiego 27, 50-370 Wrocław, Poland, E-mail: zbigniew.leonowicz@pwr.wroc.pl.*