Wavelets an Hilbert Transform methods for detection of voltage dips and micro interruptions

DRAFT

M. Caciotta, *Member, IEEE*, S. Giarnetti, F. Leccese, Z. Leonowicz, *Member, IEEE*, J. Rezmer, P. Janik

Abstract— In electrical energy power network, disturbances can cause problems in electronic devices therefore their monitoring is fundamental in Power Quality field both to properly dimension protections and to calculate compensations in case of malfunction of the apparatus. In this paper we address the problem of disturbances estimation by using two different signal processing methods such as Wavelets processing and Hilbert Transform (HT). This last is employed as an effective technique for tracking the voltage in distribution systems. The mathematical simplicity of the proposed technique, compared with the commonly used algorithms from the literature, renders them competitive candidate for the on-line tracking of disturbances. The accurate tracking of the HT facilitates its implementation for the control of disturbances mitigation devices. Simulation results are provided to verify the tracking capabilities of the HT and to evaluate its performance as pre-processing for an embedded system. Two algorithms have been tested on voltage dip under different conditions of noise and voltage harmonic distortion (THD) realizing a comparison between them that shows that the Hilbert Transform can be used as a valid methodology for this type of phenomena.

***Index Terms*—Power Quality, Wavelets, Hilbert Transform, voltage dips, micro interruptions.**

I. Introduction

Electric power quality has became an important part of power systems and electric machines, 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 [4,5,6,7,8,9,10,11,12] with emerging perspective of the Perceived Power Quality [13,14,15]. For this purpose

M. Caciotta is with Roma Tre University. Italy (e-mail: caciotta@iuniroma3.it).
S. Giarnetti is with Roma Tre University. Italy (e-mail: sgiarnetti@iuniroma3.it).
F. Leccese is with Roma Tre University. Italy (e-mail: leccese@iuniroma3.it).
Z. Leonowicz is with Wroclaw University of Technology. Wroclaw. Poland (e-mail: zbigniew.leonowicz@pwr.wroc.pl).
J. Rezmer is with Wroclaw University of Technology. Wroclaw. Poland (e-mail: jacek.rezmer@pwr.wroc.pl)
P. Janik is with Wroclaw University of Technology. Wroclaw. Poland (e-mail:przemyslaw.janik@pwr.wroc.pl)

there are many of electric parameters that help to describe the phenomena as a whole are reported in standards [16]. 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 [17,18, 19]. 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 bus 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 [20]. Most of the voltage dips are the result of momentary distribution faults. The total dip event lasts generally less than 200 milliseconds with magnitude less than 50% of nominal voltage [20]. 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. A possible solution against voltage sags can be the Dynamic Voltage Restorer (DVR) which the basic function is to inject a voltage in series with the voltage supply when a fault is detected at the Point of Common Coupling.

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. Costs that can quickly grow up with the plant resetting time that can be very long. The main protection of the customer against such events is the installation of uninterruptible power supplies [2].

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 delicate computer components and shorten their life. Possible solutions to limit this problem are, as in the case of sags, the use of uninterruptible power supplies and conditioners [21].

Voltage disturbances shorter than sags or swells are classified as transients and are caused by sudden changes in the power system [21]. 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 next future because of the increase of electronic apparatus' 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 fact fast detection algorithms may produce false trip operation of the mitigation equipment.

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 web server personal computers, which are common in office or domestic environment. This allows us 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, adopts 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.

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. Chosen HT 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 [24].

This paper is organized as follows: Section II presents Wavelet algorithm for disturbances detection. In Section III, a description of Hilbert Transform methodology is proposed as an effective way for disturbance detection. In Section IV the processing of three-phase signals is presented using a complex space-phasor. The algorithms are compared under different real test conditions in Section V where the influence of point on wave, noise and THD variation is discussed. Finally, main conclusions are detailed in Section VI.

II. Wavelets Application for voltage dip Detection

Wavelet transform is a useful tool in signal analysis. 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 [22].

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

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

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

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

are its dilated and translated versions, where a and b are the dilation parameter and translation parameter respectively, $a \in R^{+} - \{0\}$, $b \in R$ [23,24].

The discrete WT (DWT), instead of CWT, is used in practice [23]. 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

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

where $a = 2^{j}$, $b = k2^{j}$, $j \in N$, $k \in Z$.

The wavelet filter *g* plays the role of ψ [22].

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* [23]. For detection of transients a multi-resolution analysis tree (Fig.

1) based on wavelets has been applied [25]. 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 MATLAB *multires* function [26] calculates the approximation to the 2^k scale and the detail signals from the 2^1 to the 2^k scale for a given input signal. It uses the analysis filters H (lowpass) and G (highpass) and the synthesis filters RH and RG (lowpass and highpass respectively) (Fig. 2).

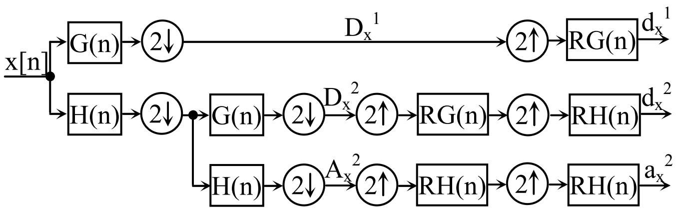

Fig. 1. Analysis-Synthesis tree for the MATLAB multires function

The decomposition can be halted at any scale, with the final smoothed output containing the information of all the remaining scales.

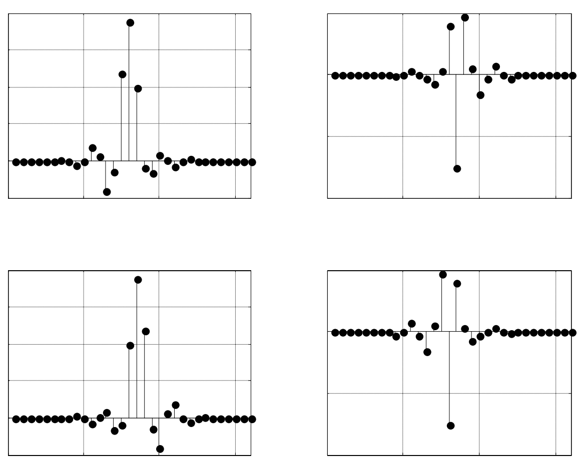

Fig. 2. Filters coefficients for symlets wavelet

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. 3). Dips detection was realized through tracking values of *details (D)* representing higher frequencies in the signal. High value indicated dip. In contrary to other presented method this approach did not use the amplitude parameter of the main component, but was therefore prone to noise and other high frequency disturbances.

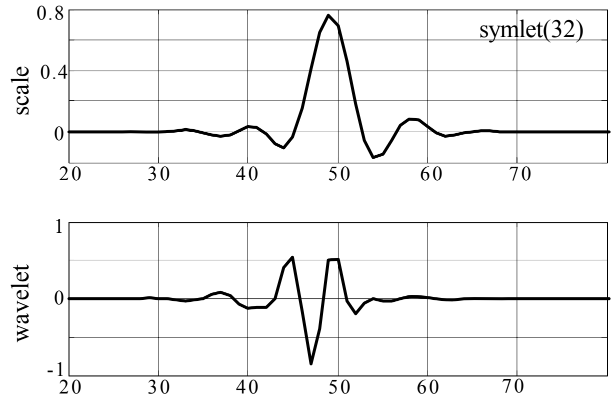

Fig. 3. Scale and wavelet symlets function for 32 coefficients

The Figure 4 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.

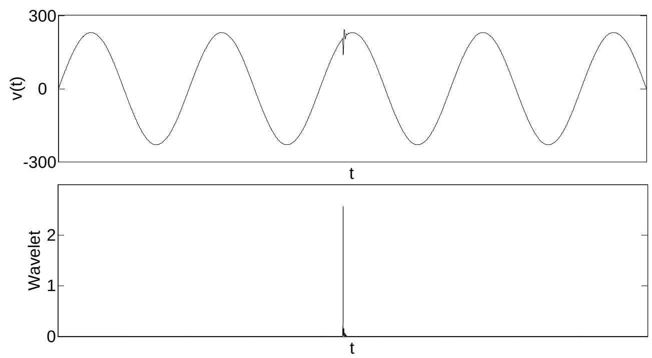

Fig. 4. Wavelet decomposition (lower plot) of the sinusoidal waveform (upper plot) distorted by one voltage dip.

III. 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 $z(t) = x(t) + j\tilde{x}(t)$ is an analytic signal. From *z(t)*, one can define a magnitude function *A(t)* and a phase function *θ(t)*, where the first describes the envelope of the original function *x(t)* versus time, and *θ(t)* describes the instantaneous phase of *x(t)* versus time.

The Hilbert transform of a real-valued function *x(t)* extending over the range $-\infty < t < +\infty$ is a real-valued function $\tilde{x}(t)$ defined by:

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

Thus $\tilde{x}(t)$ is the convolution integral of *x(t)* and *(1/πt)*, written as:

$$\tilde{x}(t) = x(t) * (1/\pi t) \quad (5)$$

Like Fourier transforms, Hilbert transforms are linear operators.

A useful point of view to understand and to compute the Hilbert Transform $\tilde{x}(t)$ of *x(t)* is using the analytic signal *z(t)* associated with *x(t)*, defined, as explained before, as

$$z(t) = x(t) + \tilde{x}(t) \quad (6)$$

that can be rewritten also as:

$$z(t) = A(t) * e^{j\theta(t)} \quad (7)$$

where *A(t)* is called the envelope signal of *x(t)* and *θ(t)* is called the instantaneous phase signal of *x(t)*. In terms of *x(t)* and $\tilde{x}(t)$, it is clear that:

$$A(t) = [x^2(t) + \tilde{x}(t)]^{1/2} \quad (8)$$

$$\theta(t) = \tan^{-1}\left[\frac{\tilde{x}(t)}{x(t)}\right] = 2\pi f_0 t \quad (9)$$

and the "instantaneous frequency" is given by:

$$f_0 = \left(\frac{1}{2\pi}\right)\tan^{-1}\left[\frac{\tilde{x}(t)}{x(t)}\right] = 2\pi f_0 t \quad (10)$$

The next Fig. 5 shows the behaviour of the Hilbert Transform decomposition of the sinusoidal waveform distorted by one voltage dip.

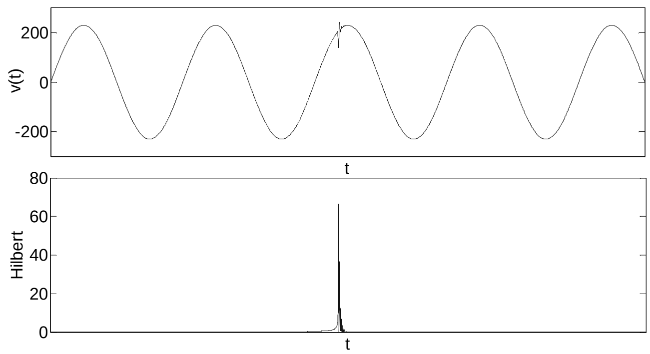

Fig. 5. Hilbert Transform decomposition (lower plot) of the sinusoidal waveform (upper plot) distorted by one voltage dip.

A Finite Impulse Response Filter (FIR) is designed to implement the HT. The HT-FIR filter can be realized in analogue or digital forms [30,31,32,33]. In this paper, the digital form of HT-FIR filter is adopted. A HT-FIR filter with odd symmetric coefficients is designed by the Parks-McClellan algorithm, which uses the Remez exchange algorithm and the Chebyshev approximation theory. The adopted method of design minimizes the maximum error between the desired frequency response and the actual frequency response. Filters that are designed in this way demonstrate an equiripple behaviour in their frequency response; hence, they are also known as equiripple filters. Fig. 1 is a block diagram of the HT for the envelope tracking. The FIR filter transfer function takes the form (7)

The filter length, *N*, affects the accuracy of the tracking of the amplitude and the speed of the calculations. The long filter length ensures a minimal tracking error, but requires more calculation time.

IV. Complex Space-phasor

Complex space-phasor $\underline{f_p} = f_\alpha + j \cdot f_\beta$ of a three-phase system f_R, f_S, f_T is given by [35]:

$$\begin{bmatrix} f_\alpha \\ f_\beta \end{bmatrix} = \sqrt{\tfrac{2}{3}} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \sqrt{\frac{3}{2}} & -\sqrt{\frac{3}{2}} \end{bmatrix} \begin{bmatrix} f_R \\ f_S \\ f_T \end{bmatrix} \qquad (11)$$

It describes, in addition to the positive-sequence components, existing negative-sequence components, harmonic and non-harmonic frequency components of the signal. The modulus of complex space-phasor of the three phase voltages is investigated using HT and WD allowing fast and compact analysis of the three-phase system and lowering the cost of input circuitry of the measuring system.

Fig. 6 shows the exemplary oscillatory impulse transient disturbance in a three-phase voltage system and the Fig. 7. the corresponding complex space-phasor.

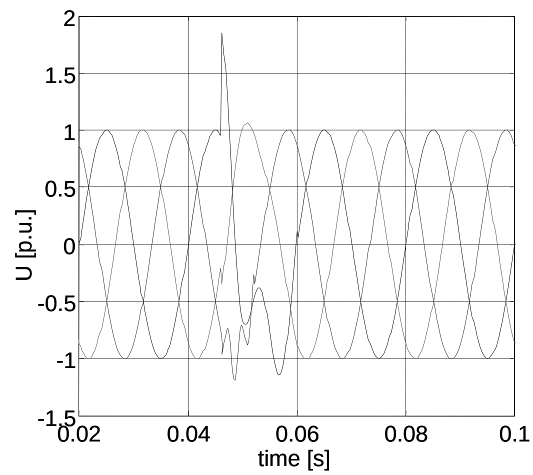

Fig. 6. Oscillatory impulse transient disturbance in 3-phase system.

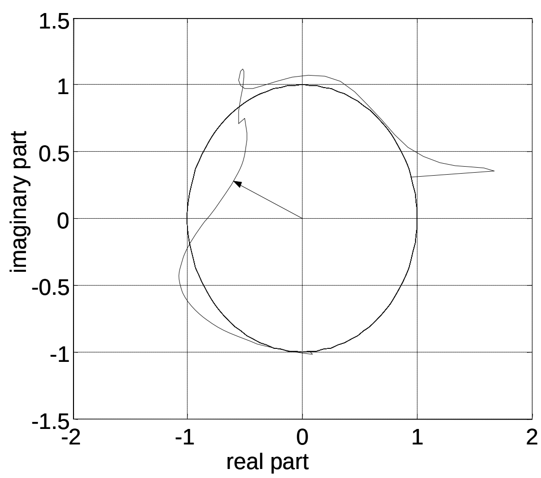

Fig. 7. Complex space-phasor of the 3-phase signal from Fig. 6.

V. Experimental Test Cases

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

For evaluating the performance of the two methods some test signals has been used with different THD and SNR. The THD used are 5.7%, 11.2% and 22.4%. These values were obtained using for each of the first 24 harmonics half of the norm limits, the norm limits, and the double of norm limits [34].

For each of the three THD has been created three signals with a different SNR: 100dB, 80dB and 60dB. The added noise is white Gaussian.

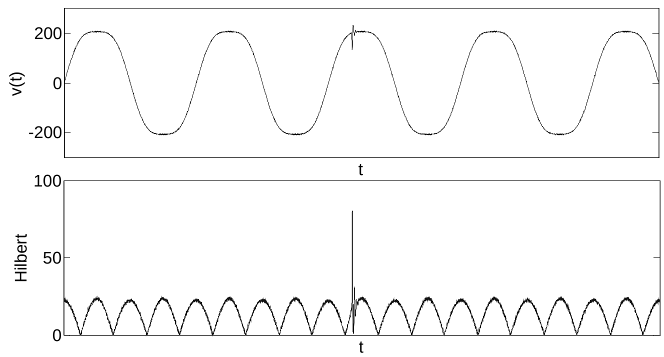

Fig. 8. Hilbert Transform decomposition (lower plot) of the sinusoidal waveform with harmonics (upper plot) distorted by one voltage dip.

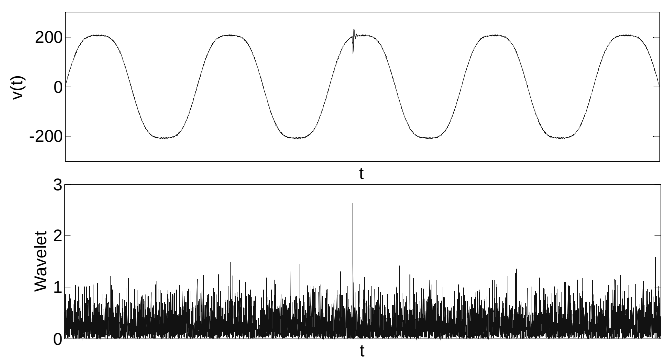

Fig. 9. Wavelet decomposition (lower plot) of the sinusoidal waveform with harmonics (upper plot) distorted by one voltage dip.

For other signals this method did not perform well. Assumingly, higher order frequency components present in the signal deteriorated the detection ability. Two wavelets with significantly different lengths have been used; *Symlet* (length of the filter 32 samples) and *Daub 6* (length of the filter 6 samples).

In the nine test signals 100 dips have been added, one for each period in randomly position. In tables 1 and 2 are reported the percentage of detect dips using HT and Wavelet for 35V and 100V dips respectively 15% and 43% of nominal voltage.

TABLE I

WAVELET AND HILBERT TRANSFORM BEHAVIOUR WITH 35V DIPS

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 II

WAVELET AND HILBERT TRANSFORM BEHAVIOUR WITH 100V DIPS

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 Hilbert Transform is more sensible to harmonics distortion than to noise. In the other hand the wavelet approach ensure good performance in presence of high THD, but the percentage of detected dips is strongly reduced for high noise level.

The pictures show the results of analysis of the sinusoidal signal distorted by noise and harmonics. The Figure 10 shows results for the signal distorted by harmonic (up to 24th harmonic) where the Total Harmonic Distortion (THD) is about the 50% of

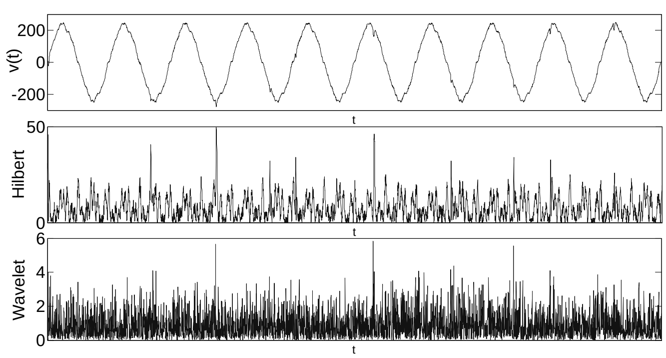

Fig. 10. Signal with harmonic and impulse distortion (upper plot) decomposition using the Hilbert Transform (middle) and wavelets (lower plot).

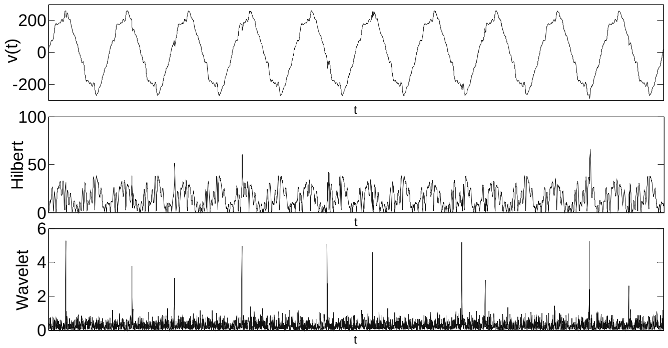

Fig. 11. Signal with harmonic and impulse distortion (upper plot) decomposition using the Hilbert Transform (middle) and wavelets (lower plot).

The Fig. 12 shows the performance of Hilbert and Wavelet Transform in the presence of different THDs and different SNRs. It is clear that the Hilbert approach is better than Wavelet only in case of lower SNR.

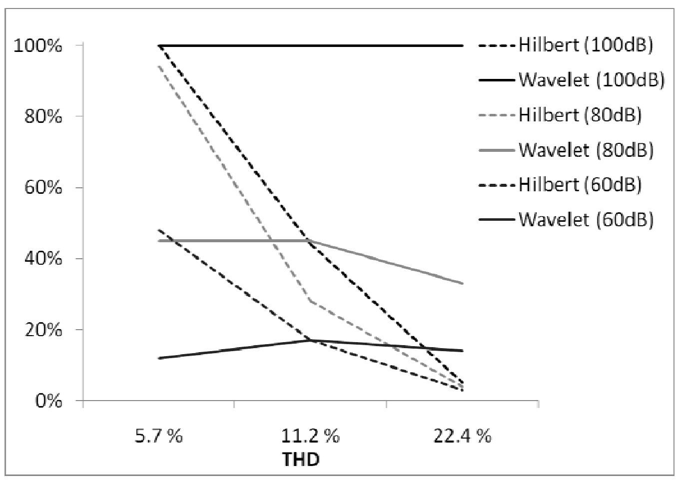

Fig. 12. Comparison between Hilbert Transform (dashed line) and Wavelet (solid line) for three different SNR values and THD percentages.

VI. Conclusion

The necessity for the modern electronic apparatus' to limit the effects of disturbances is fundamental for their correct work so the investigation of this parameter is necessary. This paper has investigated two voltage dip and micro interruptions detection algorithms such as Wavelets transform of signals and Hilbert transform. The performance of the amplitude estimations methods is compared in relation to the time it takes to each detection algorithm to estimate the beginning of the voltage dip. Both methods allow a good evaluation of the dip 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; moreover, it is able to respond within 1 ms for deep sags and swells, while for low voltage depth it takes up to 4 ms.

With the idea to mitigate the disturbances the behaviour of the algorithms are acceptable since the voltage dips with largest magnitude require the fastest response.

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