Time labelling for fast transients

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Abstract—Among the different PQ disturbances voltage sags and interruptions are the most frequent. Those disturbances typically involve even high costs for customers, mainly due to the various damages on equipment, services un-availability, product losses, recovery time, and re-start procedures. It is possible, in actual PQ monitoring applications, to utilize as timing reference in multi-location monitoring activities GNSS (Global Navigation Satellite Systems) reference. A novel wavelet technique is proposed for detecting fault in power systems.

This paper presents the characterization of transients resulting from faults in power systems using the Discrete Wavelet Transform (DWT). This characterization will aid in the development of a method for localize and find faults in a power system. The analyzed case study is obtained by simulations of different fault locations.

Keywords: Transient, Wavelet transform, Travelling wave, Fault, Power quality.

I. Introduction

Accurate fault location, i.e. to better than +/- 300 meters, was identified as a fundamental element in power transmission systems protection to improve system availability by reducing restoration times for permanent faults and identifying areas of recurrent faults. The decision to actually adopt also travelling wave fault locators (TWFL) techniques, as accurate discrimination system, is based on recent advances in digital electronics, data communications and the availability of GNSS timing. An improvement on both critical aspects of PQ investigation and power system protection can be obtained by a development of a common basic tool of Waveform Analysis for Voltage Transient Propagation Timing (VTPT). This tool is based on voltage transient reference time estimation under GNSS synchronization. For the PQ investigation the improvement will be the possibility of evaluation of PQ event causes (e.g., capacitor switching upstream or downstream from monitor position) and/or the correlation of events caused by ordinary switching operations. For the system protection, instead, the improvement will be the extension of TWFL technique to distribution systems (e.g. urban areas).

In this work a novel wavelet technique is proposed for transient characterization in power systems. In particular this paper present the time labelling characterization of fast transients in power systems using the discrete wavelet transform (DWT).

Wavelets localize the information in the time frequency plane. Due to the wide variety of signals and problems encountered in power engineering, there are various applications of wavelet transform. In this case the application of DWT to power disturbance signals it is considered useful because the information of interest is often a combination of features that are well localized temporally and spatially such for power system transients. This requires the use of analysis methods which are versatile to handle signals in terms of their time-frequency identification and localization. The wavelet transform decomposes transients into a series of wavelet components, each of which corresponds to a time domain signal that covers a specific octave frequency band. Such wavelet components appear to be useful for detecting, localizing, and classifying the sources of transient. Hence, the wavelet transform is feasible and useful for analyzing power system transients.

II. Analysis of transients by WAVELET TRANSFORM

Wavelet theory is the mathematics, which deals with building a model for non-stationary signals, using a set of components that look like small waves, called wavelets. It has become a well-known useful tool since its introduction, especially in signal and image processing.

The analysis of the transient and time varying nature of the disturbances in power systems even more considers signal processing techniques for detection, localization, and classification purposes. Recently the wavelet transform have been frequently utilized in the study of power quality [1,2,3] and protection systems [4,5] which are characterized by the "time & scale" localization of the transient signals.

A. Continuous Wavelet Transform

Considering a time series, X_n, with equal time spacing Δt and $n = 0 ... N-1$. Considering a wavelet function, $\psi_0(\eta)$, that depends on a non-dimensional time parameter η. This function must have zero mean and be localized in both time and frequency domain.

The wavelets are generated from a single basic wavelet $\psi(t)$, namely "mother wavelet", by scaling and translation:

$$\psi_{s,\tau}(t) = \frac{1}{\sqrt{s}} \psi\left(\frac{t-\tau}{s}\right) \tag{1}$$

In (1) s is the scale factor, τ is the translation factor and the factor $s^{-1/2}$ is for energy normalization across the different Scales [6].

B. Discrete Wavelet Transform (DWT) and Multi-Resolution Analysis (MRA)

The wavelet transform is a tool that divides up data, functions or operators into different frequency components, and then studies each component with a resolution matched to its scale. In particular the multi-resolution analysis (MRA) is used in this paper. The objective of multi-resolution analysis is to develop representations of a sophisticated signal *f(t)* in terms of wavelet and scaling function. Multi-resolution analysis was formulated based on the study of orthonormal, compactly supported wavelet bases.

The scaling coefficients (approximations) can be computed by taking the inner products of the function $f(t)$ with the scaling basis:

$$c_{j,k} = \left\langle f(t), \phi_{j,k}(t) \right\rangle = \int_{-\infty}^{+\infty} f(t)\phi_{j,k}(t)dt \qquad (2)$$

The wavelet coefficients (details) can be computed by taking the inner products of the function $f(t)$ with the wavelet basis:

$$d_{j,k} = \left\langle f(t), \psi_{j,k}(t) \right\rangle = \int_{-\infty}^{+\infty} f(t)\psi_{j,k}(t)dt \qquad (3)$$

where scale function $\phi_{j,k}(t)$ and wavelet function $\psi_{j,k}(t)$ is determined by the selection of a particular mother wavelet $\psi(t)$ and the following equations:

$$\phi_{j,k}(t) = 2^{j/2}\phi(2^j t - k)$$
$$\psi_{j,k}(t) = 2^{j/2}\psi(2^j t - k) \qquad (4)$$

The schematic diagram of DWT is shown in Fig. 1.

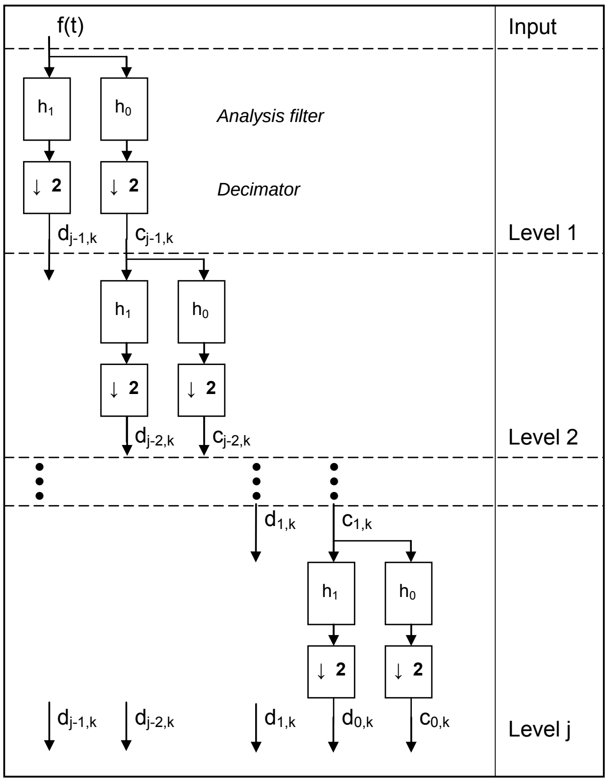

Fig. 1. Multi Resolution Analysis of Discrete Wavelet Transform (DWT)

In the discrete wavelet transform, resolution scale is commonly used to represent the degree of resolution.

The resolution scale in each resolution level is defined as:

$$scale_{Level} = 2^{Level} \qquad (5)$$

In each resolution level, the input signal d_{j+1}, in the upper resolution level is split into the approximation c_j by a lowpass filter h_0 and the detail d_j by the highpass filter h_1 in the lower resolution level. Both of output approximation and detail signal are then decimated by 2. Based on the Nyquist theorem (which states that the highest frequency which can be accurately represented is less than one-half of the sampling rate), the maximum frequency of original signal $f(t)$ sampled at $freq_{f(t)}$ Hz is $freq_{f(t)}/2$ Hz. The first approximation c_{J-1} and first detail d_{J-1} in resolution level 1 are sampled at half of $freq_{f(t)}$. Therefore, the maximum frequencies $freq_{Level}$ of signals c_j and d_j in each resolution level are given in equation 6:

$$freq_{Level} = \frac{freq_{f(t)}}{2^{Level}} \qquad (6)$$

Since the boundary of lowpass and highpass filter is half of Nyquist frequency, the upper boundary frequency of lowpass filter h_0 and the lower boundary frequency of highpass filter h_1 is the same as half of $freq_{Level}$. Therefore, the lower boundary frequency $freq_{Lower}$ and upper boundary frequency $freq_{Upper}$ of both lowpass filter h_0 and highpass filter h_1 in each resolution level are defined as:

for lowpass filter

$$freq_{Lower} = 0$$
$$freq_{Upper} = \frac{freq_{f(t)}}{2^{Level+1}} \qquad (7)$$

or highpass filter

$$freq_{Lower} = \frac{freq_{f(t)}}{2^{Level+1}}$$
$$freq_{Upper} = \frac{freq_{f(t)}}{2^{Level}} \qquad (8)$$

Scale coefficients and wavelet coefficients $coeff_{signal}$ representing the distorted signal $f(t)$ at different resolution levels in multi-resolution analysis (MRA), are defined as:

Low Frequency Range ⇒ High Frequency Range

$$coeff_{signal} = \left[c_0 \mid d_0 \mid d_1 \mid .... \mid d_{J-2} \mid d_{J-1}\right] \qquad (9)$$

where J is maximum level in this multi-resolution analysis and c_0 and d_j are the approximation in level 0 and the detail in level j respectively [7].

III. Case Study

A low voltage line (220 V, 50 Hz), simulated by Matlab-Simulink SimPowerSystem, it is used to illustrate the technique. The network shown in Figure 2 is composed by: three distributed parameter lines; and a disturbance generator based on a measurement of a Real Voltage Transient (RVT) occurred during a switching operation. The detail of such voltage transient is represented in Figure 3, where a sampling step of $4{\cdot}10^{-7}$ seconds and a total of 512 samples are considered.

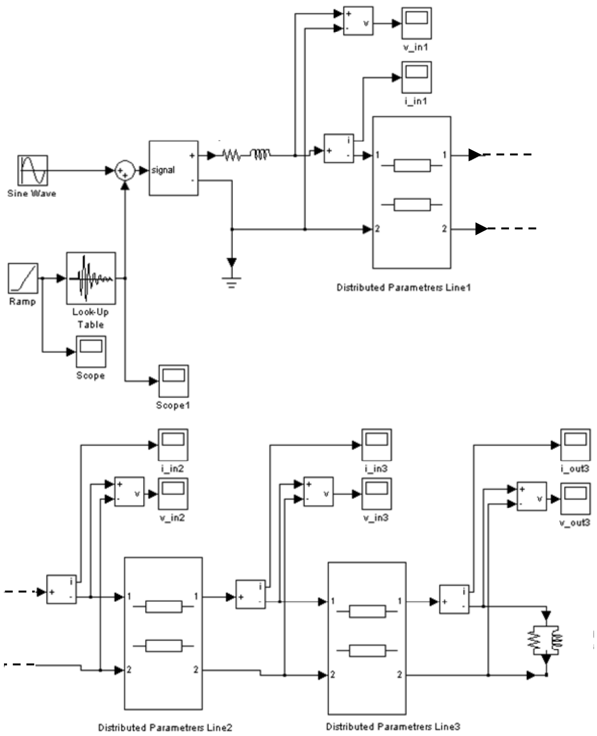

Fig. 2 : Network with real voltage transient

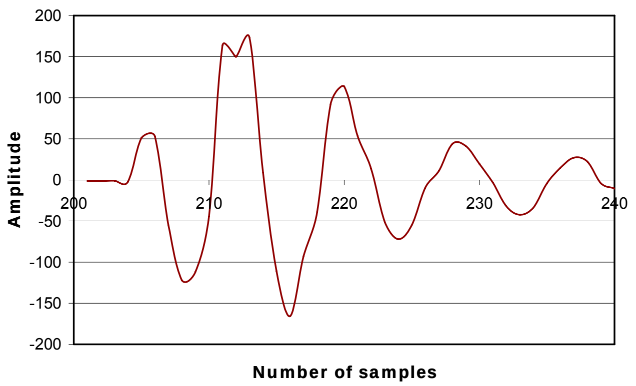

Fig. 3 : Particular of the RVT (sample step $4{\cdot}10^{-7}$ s).

A. Purpose of the analysis

Many power quality events and/or fault occurrences are associated with voltage transients. Such transients can have impulse shape or oscillatory shape.

When the knowledge of the origin of the voltage transient is the main technical interest is it is possible to use travelling wave recognition technique. But if it is necessary to recognize between very near locations, such as in sub-distribution grid, the time resolution requirements can be very small (from 10 to 100 nanoseconds).

In that case two main problems have to be solved:

– the realization of a synchronization system with enough accuracy;
– the time stamping of the voltage transient with low sensibility to the transient shape smoothing due to the transmission losses and non-linearity.

The above mentioned very critical requirements can be mitigate considering that it is possible to have differential comparison instead absolute evaluation, both for time and for transient shape time stamping.

The differential time accuracy can be improved by GNSS based timing systems and special algorithm such as Common View.

The time stamping by comparison of two transient registrations is the main argument of this paper. In particular a technique is proposed to compare wavelet transform of the actual voltage transient recorded in two point of the grid.

B. Wavelet analysis

The transient disturbance generated is decomposed by wavelet transform into several detail coefficients and approximations.

The wavelet mater is the Daubechies of order 1, or Haar wavelet.

All the graphics presented in the following have the time axis expressed in samples number instead of seconds.

For the full RVT, injected on the model shown in Fig. 2, are been considered 512 sample, with sample time equal to $4{\cdot}10^{-7}$ seconds.

Because we take 512 samples the decomposition of the signal continues for 9 levels.

The wavelet transform of the RVT, Fig. 4, shows how the fundamental frequency is [0.156 , 0.312] MHz (3° level of decomposition).

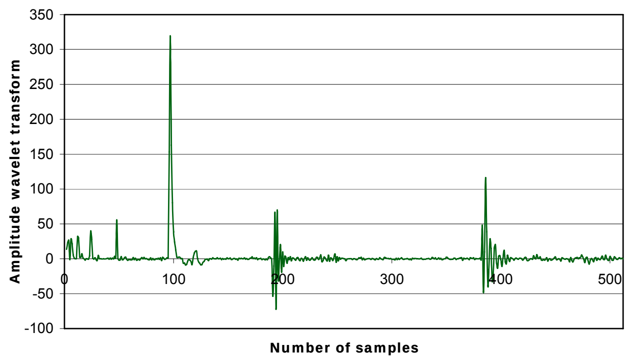

Fig. 4: Wavelet Transform of the signal

For the propagation study, instead of 512 samples and sample time equal to $4{\cdot}10^{-7}$ seconds, all signals analysed are represented by 2048 sample, with sample time equal to $1{\cdot}10^{-8}$ seconds.

Because in this case we take 2048 samples the decomposition of the signal continues for 11 levels.

Figures 5,6,7,8 show the voltage of the four buses. We can see the transient waveform deformation due to the line propagation.

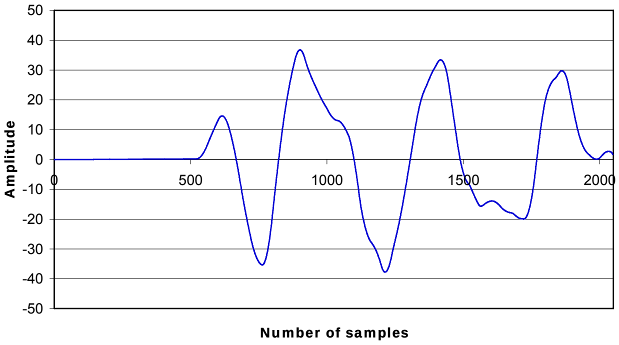

Fig. 5: Input voltage for the first line, V in1.

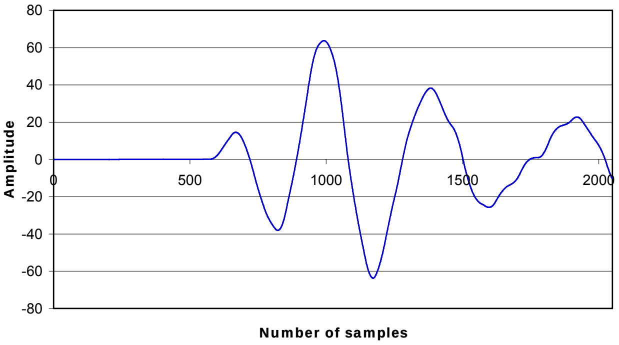

Fig. 6: Input voltage for the second line, V in2.

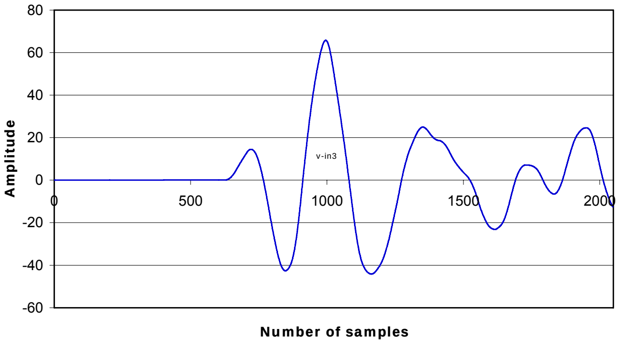

Fig. 7: Input voltage for the third line, V in3.

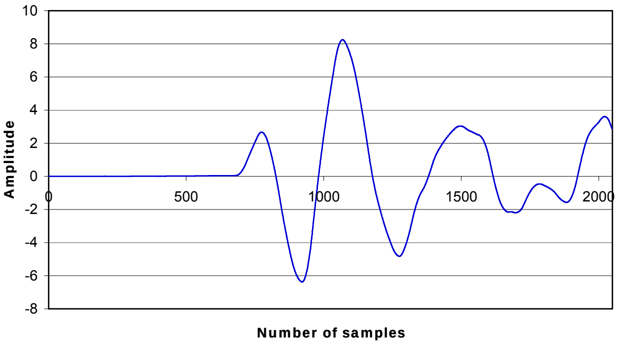

Fig. 8: Output voltage for the third line, V out3.

For our case study the availability of 2048 samples achieves to 11 levels of decomposition and the analyzed frequencies are (for the wavelet theory and sampling step of $1 \cdot 10^{-8}$ s) [50 , 25, 12.5 , 6.25 , 3.125 , 1.562 , 0.781 , 0.390 , 0.195 , 0.097 , 0.048 , 0.024] MHz.

The Discrete Wavelet Transform applied to the voltage transients represented in Figures 5,6,7,8 produces four matrix of results; each matrix (called the "scalogram") is composed of 2048 columns (one for each time step or sample) and eleven rows (one for each frequency range). Each element of the matrix is the amplitude coefficient for that frequency range and that time (or sample).

C. Time difference evaluation

From the "scalogram" it is possible to separate a number of bi-dimensional sections, one for each frequency range, representing the time-frequency amplitude distribution.

Figures 9, 10 show the Time-Frequency amplitude for the first line; figures 11, 12 show the Time-Frequency amplitude for the second segment line; figures 13, 14 show the Time-Frequency amplitude for the third segment line. All figures show how the frequencies travel in the time along the net, travelling towards right since the fault has been generated at the beginning of the net.

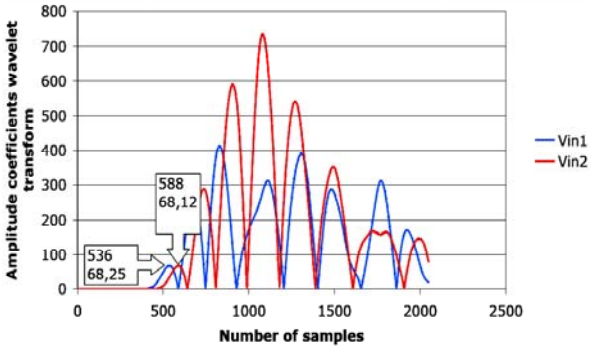

Fig. 9: Comparison Frequency (0.390 MHz) distributions for first line

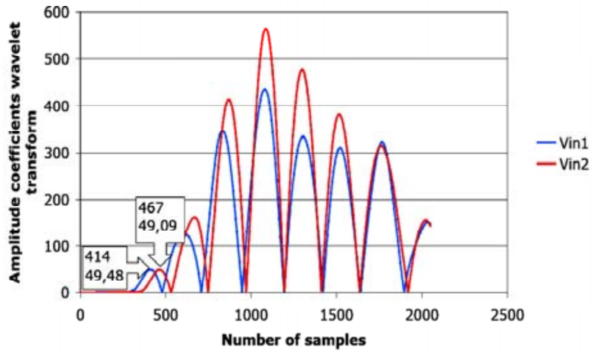

Fig. 10: Comparison Frequency (0.195 MHz) distributions for first line

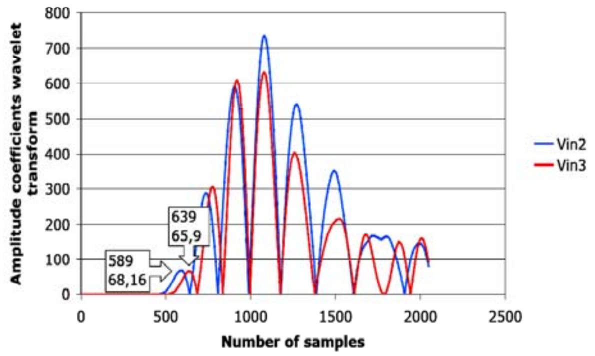

Fig. 11: Comparison Frequency (0.390 MHz) distributions for the second line

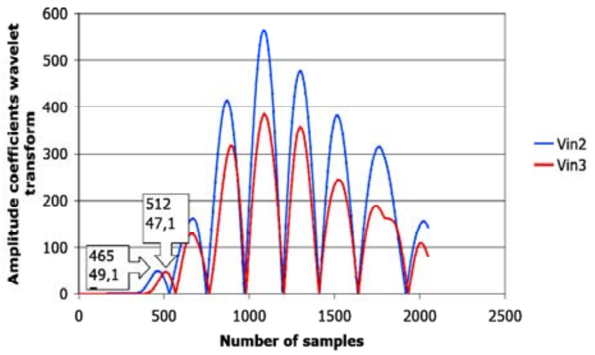

Fig. 12: Comparison Frequency (0.195 MHz) distributions for the second line

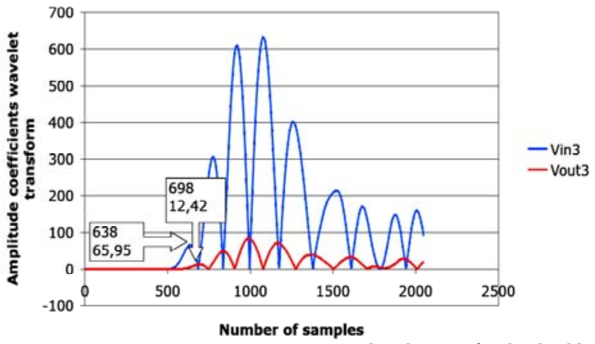

Fig. 13: Comparison Frequency (0.390 MHz) distributions for the third line

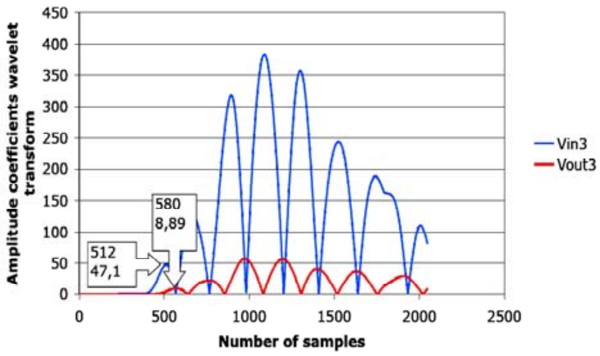

Fig. 14: Comparison Frequency (0.195 MHz) distributions for the third line

The evaluation of the transient origin is then performed to state if the same transient origin is outside or inside each couple of bus.

This evaluation is based on estimation of time difference of transient occurrence:

- if the time difference is equivalent to the propagation time of the line, the transient origin is outside the bus with t_{min}, or very near the same bus;
- if the time difference is less than the propagation time of the line, the transient origin is between the two bus and we can estimate its distance by:

$$x = \frac{L - V(t_b - t_a)}{2} \tag{10}$$

where:
L is the length of the line;
V is the line characteristic speed.

The difference of time is determined applying an opportune mathematical operation of correlation between the voltage of input and output of each line.

This difference of time estimation can be performed for all the characteristics frequency of the transient with an increased results confidence.

Figures 19, 20 show the correlations between Vin1 and Vin2, for 0.390 and 0.195 MHz respectively. The maximum of the function is consistent to the estimation of the time delay of transient propagation between the two points.

This is the expected results of differential time stamping, we can know the difference between the presentation times of the voltage transient in two bus.

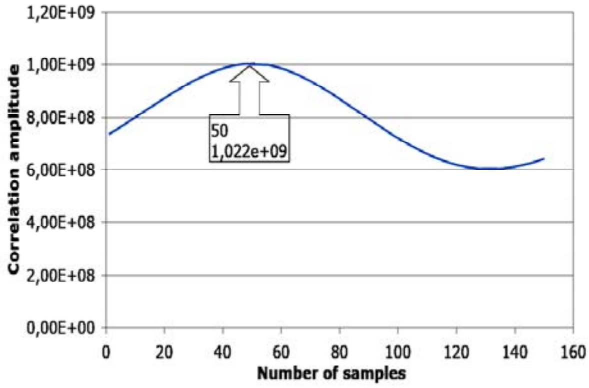

Fig. 15: Correlation between first line Frequency (0.390 MHz) distributions .

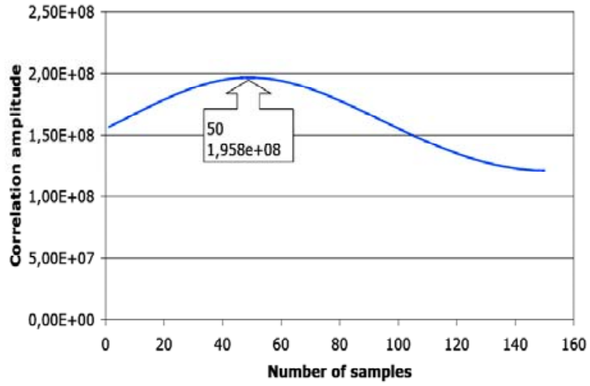

Fig. 16: Correlation between first line Frequency (0.195 MHz) distributions.

In this case we have:

$$\begin{aligned} \Delta t_{0.390MHz} &= 50 \cdot 10^{-8} s = 0.50\ \mu s \\ \Delta t_{0.195MHz} &= 50 \cdot 10^{-8} s = 0.50\ \mu s \end{aligned} \tag{11}$$

Figures 21, 22 show the correlations for the third segment between Vin3 Vout3, for 0.390 and 0.195 MHz respectively.

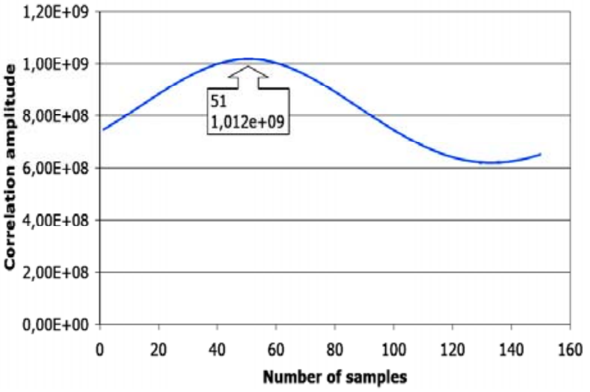

Fig. 21: Correlation between Frequency (0.390 MHz)-Time for the third segment of line.

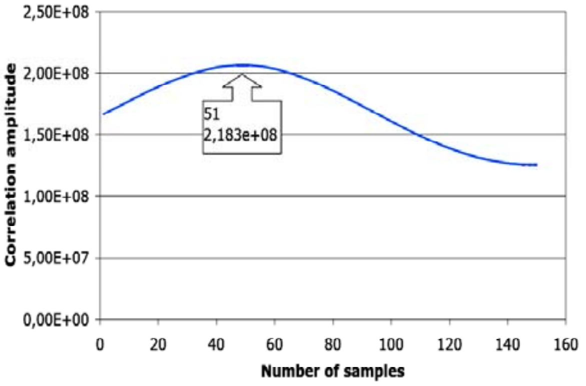

Fig. 22: Correlation between Frequency (0.195 MHz)-Time for the third segment of line.

In this different case we have:

$$\Delta t_{0.390MHz} = 51 \cdot 10^{-8} s = 0.51\,\mu s$$

$$\Delta t_{0.195MHz} = 51 \cdot 10^{-8} s = 0.51\,\mu s \qquad (12)$$

The transient time labelling characterization has than been satisfactory performed, considering that in both cases the transient origin is outside and the theoretical time propagation for the simulated lines is Δt = 0.53 μs.

IV. CONCLUSION

This paper presents a time-frequency characterization of voltage transients in electrical distribution systems based on discrete wavelet transform. The study involved wavelet theory and computer simulation of power system for fault location, studying the propagation of the frequencies in the time. The accuracy performed seems satisfactory for transient origin recognition.

V. REFERENCES

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VI. BIOGRAPHIES

Umberto Grasselli is born in Rome, Italy, on April 12, 1953. He received his degree in Electrotechnical Engineering from the University of Rome "La Sapienza" cum laude in 1978. From 1978 to 1981 he has been titular of research contract. From 1982 to 1998 he has been Assistant Professor at the University of Rome. From 1998 he is Associate Professor of Electrical Power Systems. His research activities are in the fields of power systems, planning for commercial and industrial power systems, aerospatial power systems, demand-side management, electrical design, and system reliability analysis. He has authored or co-authored of more than 90 technical papers. He is a member of the National Electrotechnical Committee CEI/CT97 and delegate to CENELEC/TC 97 and to IEC/TC 97.

Daniele Di Erasmo is born in Amelia (Terni) Italy, on March 13, 1978. He graduated at the University of Rome “La Sapienza” in Engineer Aerospace.
He has studied the analysis for not stationary signals with the wavelet theory for possible application in the monitoring of electrical nets with global navigation satellite systems.