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A VXI power quality analyser implementing a wavelet transform-based measurement procedure

L. Angrisani[a], P. Daponte[b,*], M. D'Apuzzo[c], A. Pietrosanto[a]

[a]*Dip. di Ingegneria dell'Informazione ed Ing. Elettrica, Università di Salerno, Via Ponte don Melillo, 1, 84084 Fisciano (SA), Italy*
[b]*Facoltà di Ingegneria, Università del Sannio, Palazzo Bosco-Lucarelli, Piazza Roma, 82100 Benevento, Italy*
[c]*Dip. di Ingegnaria Elettrica, Università di Napoli 'Federico II', Via Claudio 21, 80125 Napoli, Italy*

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Abstract

This paper deals with an analyser for real-time detection and analysis of transients. In particular, the analyser implements a procedure, based on the wavelet transform, suitable for analysing those disturbances which affect the power supply voltage. It utilises a good performance digital signal processor and adopts the VXI standard interface.

The hardware and software solutions are described in detail. Both performance and reliability of the analyser are assessed by analysing signals characterised by different disturbances with known characteristics; the obtained results are given.
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1. Introduction

As is well known, the detection and analysis of transient signals is needed in various application fields such as radar and sonar detection, and image processing as well as in power quality inspection [1].

With reference to the last field, in particular, the need for measurement procedures and apparata able to detect and analyse transient disturbances (impulses, notches, voltage dips and momentary interruptions, wavefaults) which frequently occur with supply voltages, and cause both failure and malfunctioning of electronic equipment [2–5], has become more and more stringent.

Currently, only high performance data loggers are available on the market which, although able to collect large amounts of measured data related to the signals under analysis, allow the detection of only those disturbances which cause the signal rms value to exceed a fixed threshold. At the end of the recording, they give the number and times of occurrence of the detected disturbances. Some of them have also analysis capability, generally restricted to harmonics [6]. This kind of approach, working under the assumption that the original time-domain signal is periodic in nature, has difficulties in dealing with transient disturbances.

Some authors have recently proposed the use of

*Corresponding author. Tel.: +39-824-305-817; fax: +39-824-21-866.

E-mail addresses: leo@diiie.unisa.it (L. Angrisani), daponte@unina.it (P. Daponte), dapuzzo@unina.it (M. D'Apuzzo)

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the wavelet transform (WT) for the analysis of transient disturbances [7–9]. The WT, based on a bidimensional approach involving both time and frequency, allows a focusing on short time intervals for high frequency components and long time intervals for low frequency components, thus improving the analysis of signals characterised by localised impulses and oscillations.

However, the proposed solutions either pay attention only to specific disturbances [8], or require a large number of parameters to be considered for establishing suitable criteria for disturbance detection and classification [9].

In a previous paper [10], the authors have optimised the use of the WT for power quality analysis. In particular, an off-line procedure able to detect, localise and estimate transient disturbances was set up. This procedure, based on multiresolution signal decomposition and reconstruction [11], obtained by means of the discrete time wavelet transform (DTWT) [12–14], succeeds in extracting the disturbance from the fundamental thus giving also the opportunity of a reliable disturbance classification [9].

In this paper, an analyser implementing a refined version of the above mentioned procedure for power quality analysis is proposed.

Thanks to its architecture, based on a digital signal processor (DSP), the proposed analyser is able to execute the procedure several times per second on successive time windows. The IEEE-1155 (VXI) standard interface, adopted for its high data transfer rate, assures a throughput so high that new data are continuously transmitted to the VXI controller as soon as they are provided by the analyser [15]. Moreover, to achieve high flexibility, the user software interface is developed utilising a common iconic programming language, so resulting in easy use and learning.

In the following, the most significant features of the implemented procedure for power quality analysis are first highlighted. Both the hardware architecture and software solutions of the proposed analyser are then described in detail. Its performance is assessed by analysing electrical power transient disturbances with known characteristics, and the obtained results are finally given.

2. Procedure for power quality analysis

The proposed procedure is mandated both to the detection and simple recognition of transient disturbances which occur with the supply voltage; furthermore, a direct quantitative estimation of the chief parameters characterising the disturbance is also allowed, which is easy both to obtain and automatize.

The procedure exploits the fundamental issues of signal multiresolution decomposition and reconstruction consisting of dividing the spectrum of the signal under analysis into subspectra or subbands and, then, to treat individually those subbands more useful for the purposes at hand.

Multiresolution decomposition and reconstruction of analysed signals are respectively carried out by means of the analysis and synthesis stages of the discrete time wavelet transform (DTWT). The DTWT analysis is based on two digital filters: a highpass $h_a(.)$, called the *discrete mother wavelet*, and its lowpass mirror version $g_a(.)$. Analysis is carried out by arranging these filters in a tree structure, as shown in Fig. 1a, which, in particular, reproduces a tree structure allowing the analysed signal, $s(.)$, to be decomposed in five subbands. Each step of this scheme consists of the same digital filters. By running the procedure described by the tree, successive steps operate a combination of the impulse responses of the filters encountered producing, as a result, at the central points H, MH, M, ML, four bandpass filters and, at the point L, a lowpass filter. In particular, the results of the DTWT analysis at the points H, MH, M, and ML can be expressed as

$$\mathrm{DTWT}(m,n)=\sum_{k=0}^{N-1} h_m(2^{m+1}n-k)s(k) \quad m=0,\ldots,3, \tag{1}$$

and at the point L as

$$\mathrm{DTWT}(m,n)=\sum_{k=0}^{N-1} h_m(2^{m}n-k)s(k) \quad m=4 \tag{2}$$

where $h_m(.)$, for $m=0,\ldots,4$, are the impulse responses of the five filters, N is the number of signal's samples and n is the discrete-time variable.

Similar considerations are valid for the DTWT

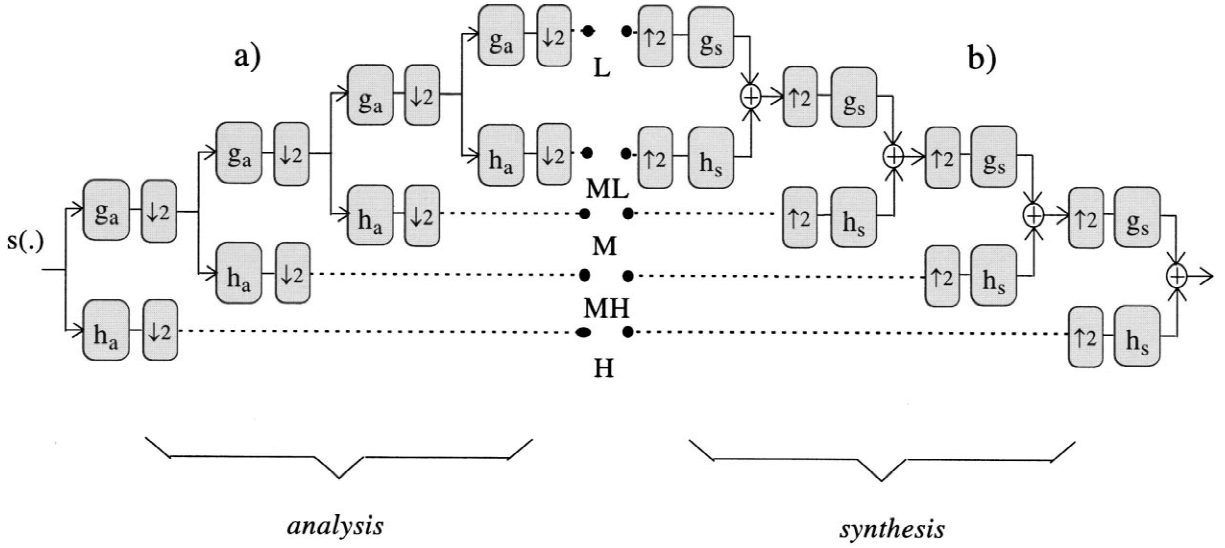

Fig. 1. DTWT analysis (a) and synthesis (b) stages.

synthesis stage, where $h_s(.)$ and $g_s(.)$ are the highpass and lowpass filters, respectively (Fig. 2b). Each input signal for the synthesis stage at the points H, MH, M, ML and L contributes to the reconstruction of the original signal. In particular, each contribution represents the time domain reconstruction of the contents of the related frequency subband.

The proposed procedure can be summarised in the following fundamental steps:

- subband decomposition of the digitised signal by means of the DTWT analysis;
- analysis of the results obtained at the point MH in order both to detect the occurred disturbance and estimate its time-duration (ΔT);
- subband identification by means of $1/\Delta T$ value, in order to single out those subbands which contain most of disturbance's spectral contents;
- reconstruction of the selected subbands by means of the DTWT synthesis stage.

The results obtained at the last step give the disturbance extracted from the signal on which it is superimposed; it is thus possible to accurately evaluate its main parameters.

A sampling frequency equal to 8400 Hz and a five subbands multiresolution scheme like that in Fig. 1 are always adopted. As a consequence, the bandwidths of the five subbands are: 2400–4200 Hz (H), 1200–2400 Hz (MH), 600–1200 Hz (M), 300–600 Hz (ML), and 0–300 Hz (L). Such choices have been made after a deep analysis of the main features of those transient disturbances which frequently occur with the supply voltage. The choices give the opportunity of (i) including only the fundamental in the subband located at the lowest frequencies (L) thus separating it from any occurred transient disturbance, and (ii) having a reduced computational load for real-time applications.

To better clarify how the procedure is carried out, an example of its application to a signal (Fig. 2a) consisting of a fundamental with a sudden notch (1.40 ms–1 V_{pp}) is given in the following.

Fig. 2b, f, l, p, t and Fig. 2c, g, m, q, u respectively reproduce the impulse responses and the spectral shapes of the five filters of the filter bank which the DTWT analysis is equivalent to [16]. Fig. 2d, h, n, r, v show the output of these filters (DTWT analysis results). From the results in Fig. 2h, the disturbance time-duration ΔT is estimated, this being the peaks of the shown waveform related to the start and end of the transient disturbance.

This time-duration is equal to 1.45 ms ($1/\Delta T$ about 700 Hz) suggesting that most of disturbance's

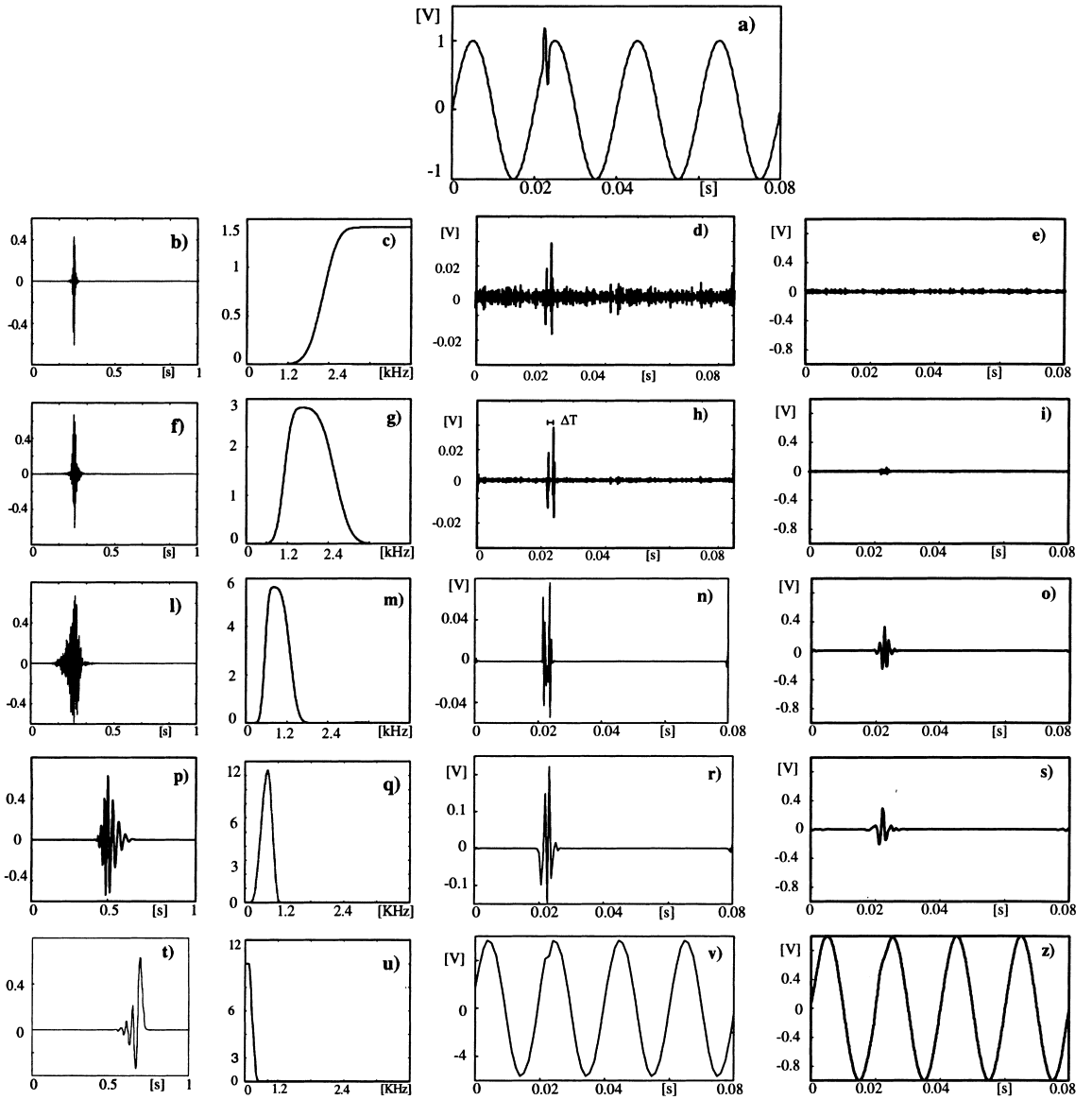

Fig. 2. (a) Signal with a disturbance; (b), (f), (l), (p), (t) impulse responses and (c), (g), (m), (q), (u) spectral shapes of the chosen filters; (d), (h), (n), (r), (v) DTWT analysis and (e), (i), (o), (s), (z) DTWT synthesis results.

spectral contents is inside the subband 600–1200 Hz (Fig. 2n). The time domain reconstruction of the contents of this subband allows both a direct recognition of the occurred disturbance and a quantitative estimation of its main parameters.

Furthermore, for a more accurate disturbance extraction it may sometimes be necessary to make use of more subbands and, in particular, of those adjacent to the selected one. As a matter of fact, summing the contents of the subband in Fig. 2o to those included in adjacent subbands, shown in Fig. 2i and Fig. 2s, respectively, the reconstructed, occurred disturbance appears as given in Fig. 3.

Finally, it is worth noting that the contents of the subband located at the highest frequencies (Fig. 2d) essentially consist of noise mainly introduced by the

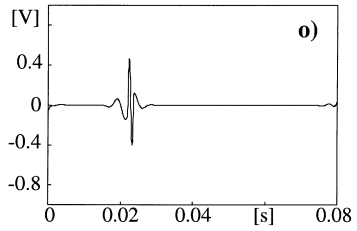

Fig. 3. Reconstruction results; the disturbance is extracted from the fundamental.

quantisation process. This justifies the choice of estimating the time-duration of the occurred disturbance from the decomposition results of the successive subband (Fig. 2h). Even though the time resolution is poorer than that characterising the highest frequencies subband, unsignificant measurements due to the presence of noise are avoided.

3. Hardware structure

The IEEE-1155 standard, well known as VXI, concerns the electrical, mechanical and functional specifications for the realisation of on-a-card instruments. As a consequence, the hardware of the analyser has been designed taking into account both measurement needs and the characteristics of the VXIbus interfaces. In particular, a VXI size-C Wire Wrap Board (Tektronix 73A-451™) [17], equipped with a Message-Based interface module, has been used as the 'bread-board' for instrument development and the constructed instrument has a general purpose architecture which allows a set of measurement features to be obtained. It has been thought out without a resident firmware, but requiring that the control and measurement software be downloaded via the DSP emulation port. Furthermore, it has been provided with a general purpose data acquisition system (DAS) which is quite redundant in this case. As a result, the proposed hardware architecture is that shown in Fig. 4. It is based on the following main blocks:

1. Data acquisition system (DAS);
2. DSP;
3. VXIbus interface circuitry;
4. Serial-parallel data converter.

1. The DAS includes a 16 bit two channel ADC (Burr Brown DSP102-A/D™) and a 16 bit two channel DAC (Burr Brown DSP202-D/A™), even though only one ADC channel should be necessary for this application. All the converters have a serial output (or input) and are directly linked to the full duplex Serial Port 0 of the DSP.
2. A 32 bit, 30 MHz, floating point DSP (Texas Instrument TMS320C30™) constitutes the core of the instrument. It features an additional 16 K static RAM and is suitably loaded and bootstrapped via its emulation port which is accessible via a suitable front-panel connector. The TMS320C30™ has been chosen for both its performance and its widespread use in numerous devices and applications.
3. The Wire Wrap Board (WWB) hosts a Message-

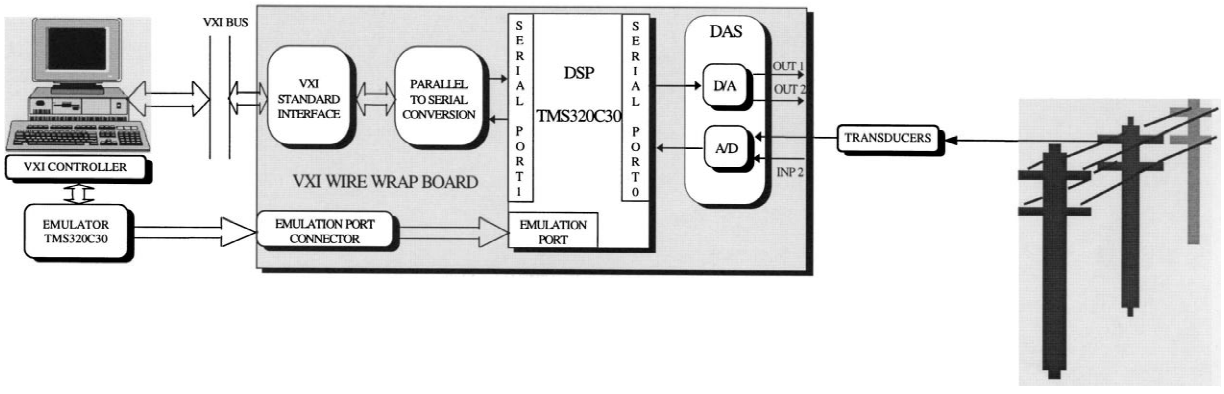

Fig. 4. Hardware structure of the proposed VXI power quality analyser.

Based VXIbus interface module which allows the analyser to exchange 8 bit data with the controller by means of the two Byte Transfer Protocol Commands: Byte Request (BR) and Byte Available (BA). Even though limited to 8 bit data transfers, the Message-Based interface was preferred to a Register-Based one both for its easy interface-ability with the instrument circuitry and its maximum compatibility with standard programming environments.

4. Custom circuitry interfaces the instrument-side user bus (parallel, 8 bit) of the VXI interface module with the DSP Serial Port 1. A series of four serial-in/parallel-out (74ALS164) shift registers, latched by four 74ALS373 which are selected one at a time by a 74ALS42 decoder, convert the serial transmitted 32 bit words from the DSP in sequences of four bytes to the user bus of the VXI interface module. A parallel-in/serial-out shift register (74ALS165), on the other hand, transmits in serial form to the DSP Serial Port 1 the 8 bit data coming from the user bus of the VXI interface module [18–20].

4. The software

The user communicates with the VXI analyser only via the VXIbus controller. As a result, two software modules have been designed: the *instrument control software* (running on the DSP), and the *user interface program* (running on the VXI controller).

4.1. The instrument control software

As far as the instrument control software is concerned, this is downloaded on the DSP by a suitable TMS320C30™ emulator, which is placed in a slot of the VXI controller and connected to the analyser via the front panel connector.

The instrument control software performs the following main tasks:

1. data acquisition;
2. power quality analysis;
3. communication with the VXI controller.

Data acquisition is continuously carried out on the basis of the last sampling frequency F_s and number of points N_p selected by the user. In each sampling period T_s, a new signal sample is acquired and transmitted by the ADC to the Serial Port 0 of the DSP. Once the Serial Port 0 input buffer is fulfilled by the received sample, an interrupt to the DSP is generated. The corresponding service routine reads the sample from the buffer and writes it in the input array. Moreover, once the input array is fulfilled, the service routine also makes a pointer swapping in order to allow the last samples to be passed to the power quality analysis procedure, before the array is loaded with new samples.

The power quality analysis procedure, based on the aforementioned wavelet transform and signal reconstruction, provides the time domain shape of the detected disturbance, extracted from the fundamental. The procedure is called by the main program which constitutes an infinite loop based on the following four steps:

- waiting for the last sample array to be available;
- executing the power analysis procedure on the acquired signal samples;
- writing the samples of the occurred disturbance in the output data array;
- processing eventual device commands or output data queries received from the VXI controller.

As for the last step, as soon as the VXIbus interface module receives either a BA or a BR command, it generates an interrupt to the DSP. The corresponding service routine immediately makes the DSP assert an acknowledgement signal to the interface module. The service routine then also determines if readings (BA) or writings (BR) are required, and finally assigns a proper value to the volatile control variable (EVENT). As a consequence, each time a new output data array is available, the main program checks the variable EVENT: if no BA or BR is pending, it then waits for a new input data array to process; otherwise, a series of either 4 byte readings or $4N_p$ byte writings are executed. The former allows a device command, sent by the user interface program and concerning new settings for the signal analyser, to be received and executed. The

latter allows the last output array (N_p floats) to be transmitted to the user interface program.

4.2. The user interface program

The user interface program is developed in the iconic programming language LabView™. It is designed for (i) sending device commands to the analyser in order to set measurement specifications, and (ii) requesting the last output array made available by the signal analyser.

The front panel appears as shown in Figs. 5–7.

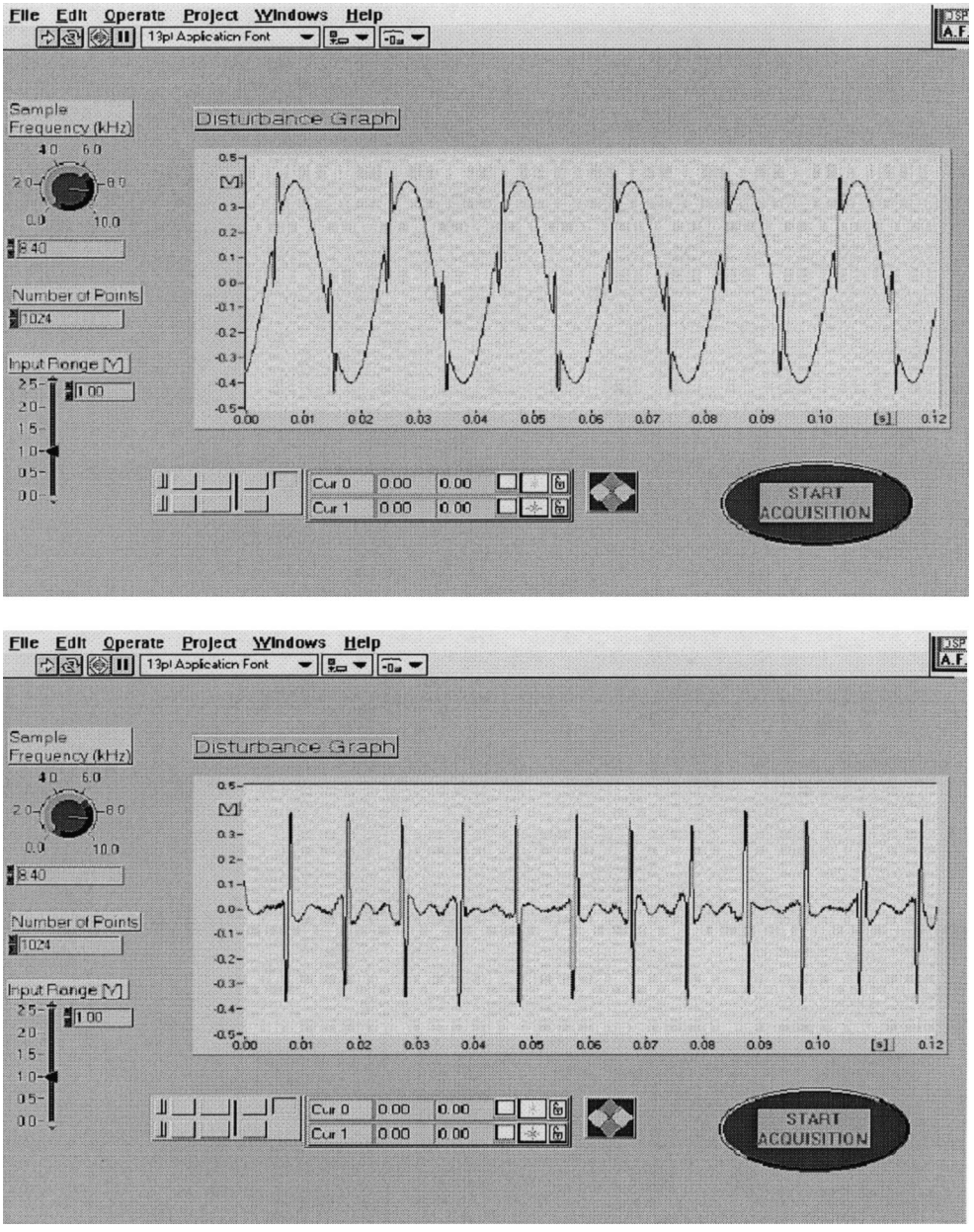

Fig. 5. Upper, a periodical notch superimposed on the fundamental; lower, reconstruction results.

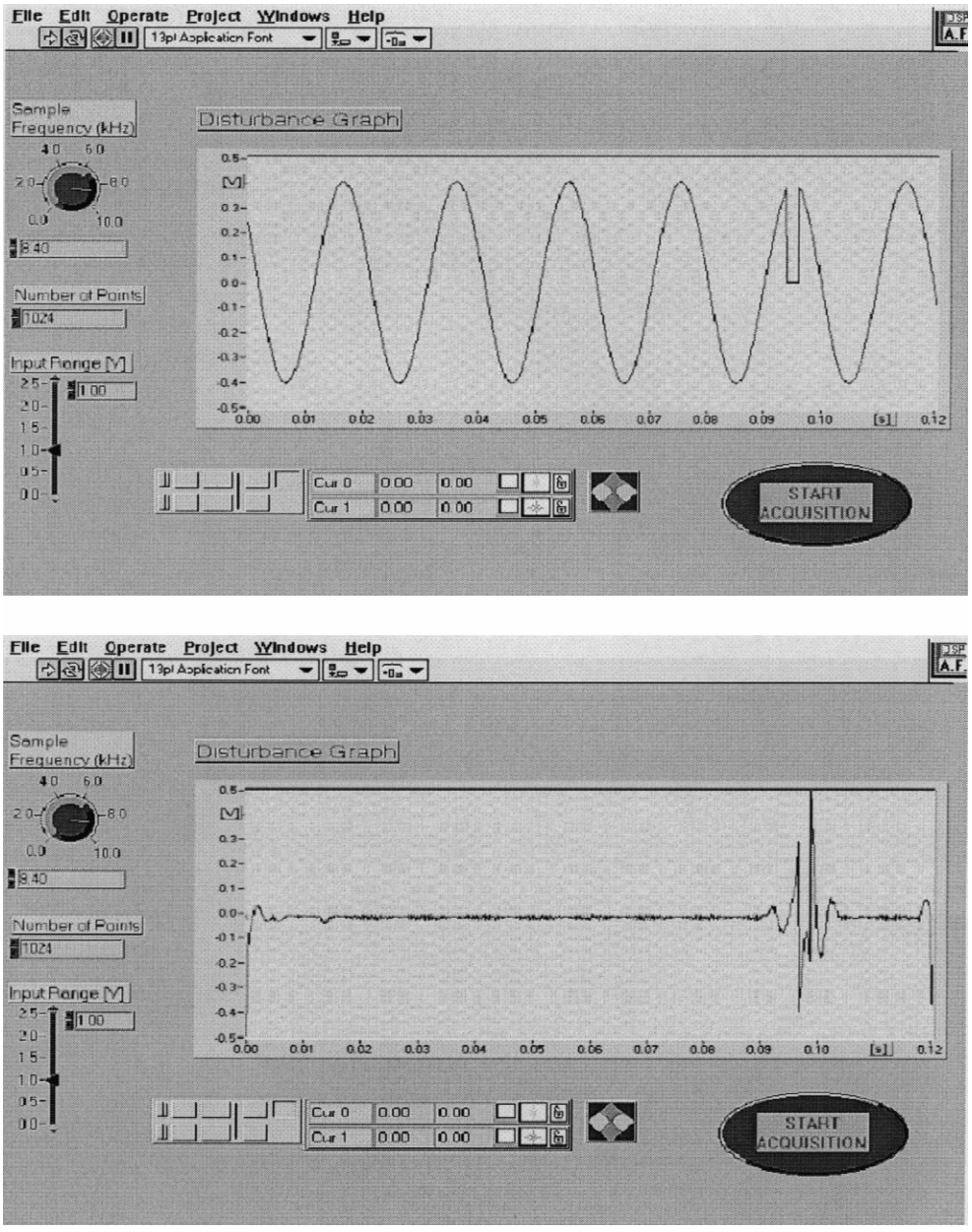

Fig. 6. Upper, a micro-interruption superimposed on the fundamental; lower, reconstruction results.

Each press of the 'Start Acquisition' button causes new results to be requested and, once received from the analyser, displayed. Other controls allow the user to choose the sampling frequency F_s, the number of points N_p and the input range to be adopted.

5. VXI power quality analyzer performance verification

After a suitable static and dynamic characterisation both of the ADC and DAC, the performance of

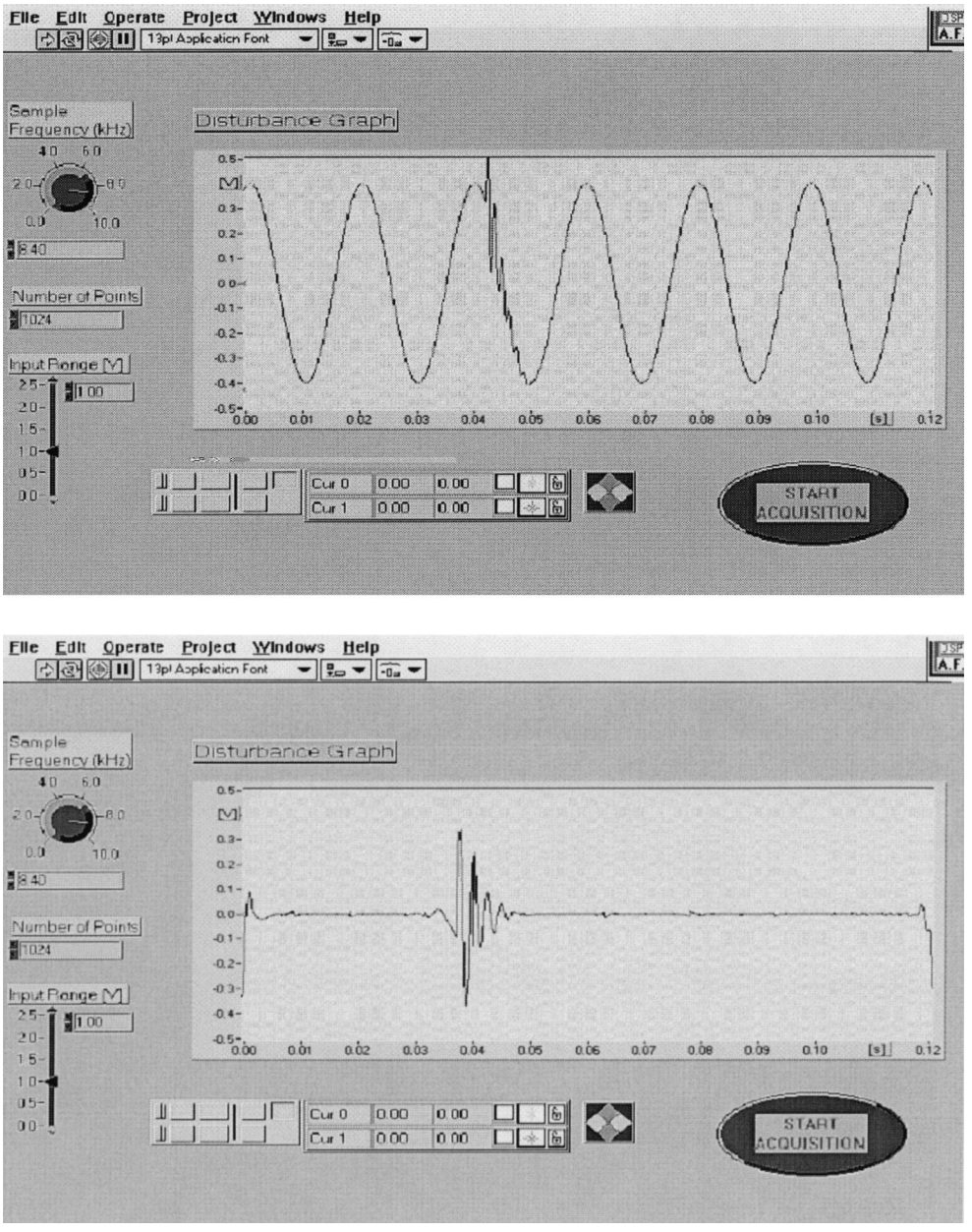

Fig. 7. Upper, an oscillatory transient superimposed on the fundamental; lower, reconstruction results.

the proposed VXI power quality analyser was assessed by analysing test signals with known characteristics. Test signals usually consist of a fundamental on which common transient disturbances are superimposed. In particular, the attention has been paid to:

1. periodic and sudden impulses or notches shaped as basic waveforms (Fig. 5 upper);
2. voltage dips and micro-interruptions (Fig. 6 upper);
3. oscillatory transients shaped as exponentially damped sinusoids (Fig. 7 upper).