A NEW INSTRUMENT FOR HARMONICS AND INTERHARMONICS MEASUREMENT FOR POWER SUPPLY SYSTEMS AND EQUIPMENT CONNECTED THERETO

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Abstract − In the last years the increased interest about power quality, forced international working groups to define new standards for testing and measurement techniques applied to power systems. A particular attention has been paid to harmonic and interharmonic measurements for the well-known problems related to different power equipments. Considering the actual state of instrumentation technology, these standards assumes that only instruments using the Discrete Fourier Transform (DFT) are likely to be designed. Moreover, also if strictly speaking the concepts for distortion analysis can be applied only to steady state signals, draft and revision standards introduce a simplified procedure to evaluate general non stationary harmonic components and in particular interharmonics. These procedures are based on a hard limit for signal synchronous sampling and on different groupings and smoothings applied to the obtained spectrum. This allows assuring a complete and standardized interpretation of harmonic and interharmonic signal pollution. In this work, Authors present a software instrument developed in accordance with all in force, draft and under revision standards and international documents (IEC 61000 Part.3, Draft IEC 61000-4-30 Ed. 2000, Draft revision IEC 61000-4-7 Ed. 2000, Draft Guide IEEE P1159.1 ed. 2000, able to perform an on line voltage or current distortion analysis. The instrument has been tested and the result is that it can be used as a reference performance instrument, then where precise measurements are necessary, e.g. verifying compliance with standards, resolving disputes or for accurate emission measurements.

Keywords: power quality, draft revision IEC 61000-4-7 ed 2000, harmonic and interharmonic analysis.

1. INTRODUCTION

In recent years, the large use of electronic devices in industrial and common applications is causing high distortion level in electric power systems, by means of introducing harmonics and interharmonics superimposed to the fundamental current and/or voltage component.

This distortion causes working life shortening, losses increasing and bad working conditions for most of power systems equipments.

Moreover, problems related to the electrical energy free trade (and then to the interface between different companies and users) has required the improvement of the regulamentation limits in power systems and then the development of different national and international standards. These documents, some of them in force, some others under revising process or still in draft state, report accurate and well defined test and measurement procedures in order to obtain reliable, repeatable and comparable results useful to analyse and to characterize power networks and equipments connected there to.

Software instruments based on digital signal processing techniques usually are cheap, user friendly and present a good accuracy; moreover, they are easily reconfigurable and can be adapted to standards progress. In these instruments, signals are usually transformed from the time to the frequency domain by means of discrete Fourier Transform algorithm, in order to evaluate energy contents of different spectral components. As it is well known the calculated spectrum is equal to the real one, only if the Nyquist theorem is respected and if the analysed signal segment is periodic and if it is an integer multiple of its period [1,2]. Usually, the presence of unstationary components in the electric power signals (i.e. interharmonics or other frequency-variable harmonics) causes, in the resulting spectrum, a leakage error (i.e. spreading of spectral bins). This error is often negligible, while that one due to signal unsynchronised sampling [2,3] cannot be similarly considered. Moreover, the first cause of leakage error can not be eliminated, while the unsynchronization, related to the signal sampling conditions can be avoided (or reduced).

On the basis of several previous works, leakage error can be reduced performing a suitable windowing operation and/or using correction interpolation algorithms [4-5]. On the other hand these methods limit but do not remove the error and require an extra computational cost.

International in force and draft Standards about testing and measurement techniques for electrical drives and power system networks refer always to [6] to perform harmonics and interharmonics measurements. In fact, this draft revision IEC standard defines all procedures and accuracy limits for harmonic and interharmonic survey up to 2 kHZ (or 9 kHz). This standardization implies a synchronous sampling assumption in order to be able considering spectral leakage reduced only to signal unstationariety. Solutions already proposed in literature to synchronize sampling can be mainly classified in analog or digital phase locked loop

(PLL) [1,7] and software solutions based on signal spectral analysis techniques (usually by means of FFT) [4-5]. Spectral analysis purpose is to evaluate fundamental signal frequency to appropriately set sampling frequency. The main drawback is that spectral frequency error is proportional to spectral resolution (i.e. the distance of two next bins) that is, for usual spectral analysis methods, the reciprocal of the observation window T_w [2]. Then, to improve frequency resolution it is necessary to consider a large time interval. On the other hand, signals cannot be considered as stationary in a long time interval because of many measured processes are brief in duration or have slowly time-varying spectral components. Moreover, in order to perform signal spectral analysis, the IEC Standards define a observation window width T_w exactly equal to 10 fundamental periods, 50 Hz power system, (12 periods, 60Hz system), of the fundamental component corresponding approximately to 200 ms (150 ms).

This setting allows obtaining a 5 Hz (6 Hz) resolution spectral analysis that means a too high error to use the evaluated fundamental frequency as reference value for sampling frequency setting. A common way to improve spectral accuracy is to apply interpolation algorithms [4-5]. These procedures recreate lobe curve by interpolating three or more next spectral bins, reducing picket fence error [1]. The main problem of these solutions is that in presence of tonal interference between spectral components, the energy of different bins is due not only to a single harmonic; this causes an error in the lobes reconstruction. Generally this error is limited and interpolation techniques can be well suited for fundamental frequency evaluation. When interharmonic distortion occurs, tonal interference increases, especially when these spectral components are near to next fundamental bins.

A possible solution to overcome this problem is to improve spectral resolution by means of zero padding technique [1]. The drawback of this method is that increasing the percentage of zeros samples in the analysed buffer (with a fixed number of signal sampled points), and then spectral resolution, lobes spectral components amplitudes decrease; moreover, this solution increases computational and memory instrumentation requirements. Moreover, it can be observed that, to perform a synchronization, it is necessary to detect only the signal fundamental frequency and therefore to analyse a limited frequency window.

In a previous work Authors presented a detailed comparison among different spectral analysis methods [8]. It has been shown how the Chirp-Z Transform (CZT) allows optimising resolution utilizing all sampled data to reconstruct signal in a fixed and limited frequency window. Moreover, Authors have presented in [9] a CZT based synchronizer, reporting a full experimental comparison to a classic interpolated FFT based one. It has been shown how the new method allows reducing the leakage error, respecting all the limits imposed by [6].

In this paper a new instrument for the harmonic and interharmonic characterization of supply systems and of the equipment connected thereto is presented and characterized;

at the end, test procedures reported in [6] have been applied to evaluate the instrument accuracy (i.e. class).

2. CZT BASED SYNCHRONIZER

In [10] Authors presented a CZT based synchronizer alternative to the commonly used ones, able to respect error limit imposed by [6] also in presence of interharmonic distortion with spectral components next to the fundamental. In fact, in these particular distortion conditions, general synchronizers are not able to maintain their accuracy.

This functional block utilizes the same buffered sampled points used for the signal distortion analyses.

The interval in which the synchronizer has to preserve its accuracy is fixed by [6] as ±5% of the nominal system frequency (47,5-52,5HZ for 50Hz; 57,0-63,0 for 60Hz); consequently, the analysed frequency band to detect the frequency of the fundamental component has been chosen 0,2 Hz larger in order to assure the lobe peak identification.

Buffer width M is set according to the wanted CZT spectral accuracy and to the accuracy fixed by [6] for the determination of the synchronization sampling frequency.

Anywhere, 4096 point allows to obtain a theorical spectral resolution equal to 0,00127 Hz [2,8], lower enough to respect [6] limits.

Synchronizer evaluates sampling frequency f_s by using the evaluated fundamental frequency f_0, so to obtain 10 sampled periods for 50Hz systems (or 12 for 60 Hz ones) as stated by [6] as reference analysis interval:

$$f_s = \frac{M \cdot f_0}{10} \tag{1}$$

As stated by the draft document, synchronization system has to check the sampling process in order to establish in which cases, procedure accuracy is not respected. In these cases, algorithm has to apply windowing (by means of Hanning function), in order to reduce leakage error, before proceeding FFT analysis.
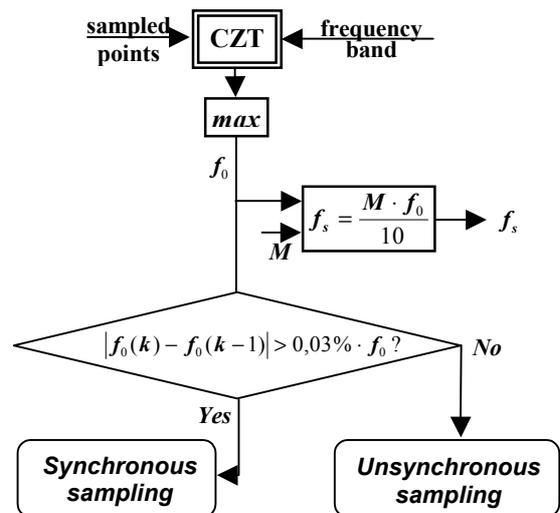
In Fig.1, the synchronizer block diagram is reported.

Fig. 1. Synchronizer block diagram.

3. HARMONICS AND INTERHARMONICS MEASUREMENT INSTRUMENT

International Standards indicate IEC 61000-4-7 as reference for testing and measurement instrumentation, for power supply systems and equipment connected there to.

In this standard (actually under revision process [6]), requirements for harmonic and interharmonic measurements are given for frequency range up to 2kHz (frequencies up to 9 kHz are also considered).

This document sets the accuracy limits, the measurement procedures and requirements for harmonic and interharmonic emission measurement; it also describes accuracy tests for developed instrumentation.

Strictly speaking, harmonic measurements can be performed only on a stationary signal, considered that fluctuating signals (signals varying with time) cannot be described correctly by their harmonics only. However, also if power signals (current or voltage) can be never considered as stationary, it is often useful obtaining their distortion analysis. For this reason, and in order to obtain results that are intercomparable, a simplified and reproducible approach is given in [6] for fluctuating signals introducing the concepts of spectral bins grouping.

The developed instrument, whose functional block diagram is reported in Fig. 3, has been based on Fast Fourier Transform Analysis as suggested by [6]. In fact, the same document assumes that only instruments using the Discrete Fourier Transform DFT are likely to be designed for this kind of measurement. The same standard does not exclude instrumentation based on different analysis techniques. Anywhere, since these procedures are not covered by this draft, it is required that such procedure does not exceed the defined range of uncertainty and, however, that such instrumentation has not to be used for assessing compliance with emission limits.

Current and/or voltage signals are transduced and preprocessed (synchronizing process); then FFT is applied in order to obtain in the output (OUT 1, see Fig 2) the values of each frequency component.
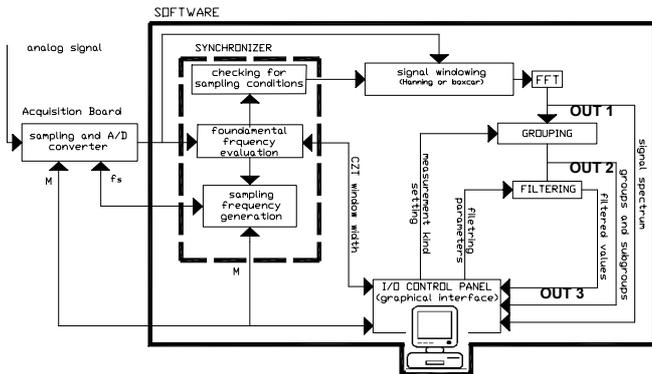

Fig. 2. Functional block diagram of the harmonic and interharmonic measurement instrument.

Instrument has been set in order to measure harmonic and interharmonic components in the range 0 to 2 kHz for 50Hz power electric systems.

Anywhere, it can be set for 60 Hs ones, easily setting nominal frequency in the control panel.

Spectral components outside this range are attenuated with an analog antialiasing filter so as not to affect the results.

To obtain the appropriate attenuation, the analysed range reach 2,5 kHz for 50 Hz system (or 3,0 kHz for 60 Hz ones), but only components up to 2 kHz (2,5 kHz) are taken into account.

According to [6] and as required by emission standards (IEC 61000 Part. 3), additional operations on the raw data (spectral bins) such as smoothing and weighting of the raw results are performed and reported at the outputs 2 and 3. These operations are widely discussed in the following paragraphs.

3.1. Grouping

The Fourier transform analysis assumes that the signal is stationary. However, voltage and current signals on power systems may fluctuate, spreading out the energy of their harmonic components to adjacent spectral bins (leakage).

To improve the assessment accuracy and to obtain comparable results, the output components c of the FFT shall be grouped according to the specifications reported in [6].

Defining a signal observation window equal to 10 fundamental periods, for 50Hz systems (12 for 60Hz ones), as required by [6], the obtained spectral resolution will be about 5Hz (6 Hz), see Fig.3.

These bins are grouped evaluating the rms in different configurations (groups or subgroups), depending on what kind of measurement is going to be performed (harmonics/ interharmonics or both of them).

These values correspond to the instrument OUT 2.

Fig. 3. General spectrum resolution according to IEC 61000-4-7 (here represented for a 50Hz system).

- *Groups*

The harmonic group component n_g (OUT 2, see Fig.2) of order n (corresponding to the centre line in the hatched area, see Fig.5.) has the magnitude C_{ng} (rms value).

C_{ng} is obtained by summing squared intermediate lines between two adjacent harmonics according to (2) for 50 Hz and to (3) for 60 Hz systems, as visualized in Fig.4.

50 Hz systems:

$$C_{n_g}^2 = \frac{c^2_{n \cdot f_0 - \frac{5}{T_w}}}{2} + \sum_{i=-4}^{+4} c^2_{n \cdot f_0 + \frac{i}{T_w}} + \frac{c^2_{n \cdot f_0 + \frac{5}{T_w}}}{2} ; \qquad (2)$$

60 Hz systems:

$$C_{n_g}^2 = \frac{c^2_{n \cdot f_0 - \frac{6}{T_w}}}{2} + \sum_{i=-5}^{+5} c^2_{n \cdot f_0 + \frac{i}{T_w}} + \frac{c^2_{n \cdot f_0 + \frac{6}{T_w}}}{2} . \qquad (3)$$

Where c_{nfo} is the value of the central bin of the FFT (OUT 1, see Fig.2) corresponding to the n harmonic and $c_{n \cdot f_0 + \frac{i}{T_w}}$ are the bins corresponding to the i spectral lines (5 on the left and 5 on the right side for 50 Hz systems, or 6 and 6 for 60 Hz ones) next to it.
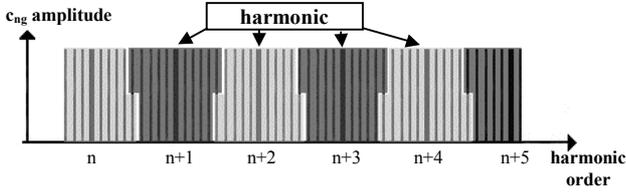

Fig. 4. Illustration of harmonic groups
(here represented for a 50Hz system).

Similar evaluation has been used for interharmonics. Moreover, interharmonic components usually vary not only in magnitude but also in frequency.

A grouping of the spectral components in the interval between two consecutive harmonic components forms an interharmonic group.

The interharmonic groups have been evaluated according to (4,5) and are graphically reported in Fig.5.

For 50 Hz systems:

$$C^2_{(n+0.5)_g} = \sum_{i=+1}^{+9} c^2_{n \cdot f_0 + \frac{i}{T_w}} \; ; \qquad (4)$$

and for 60 Hz ones:

$$C^2_{(n+0.5)_g} = \sum_{i=+1}^{+11} c^2_{n \cdot f_0 + \frac{i}{T_w}} \; . \qquad (5)$$
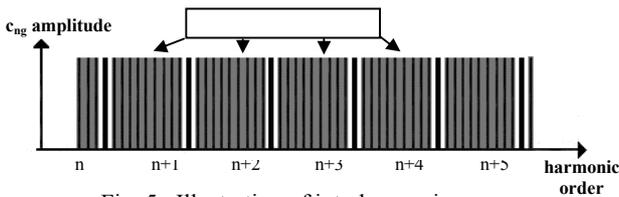

Fig. 5. Illustration of interharmonic groups
(here represented for a 50Hz system).

- *Subgroups*
If harmonics and interharmonics are evaluated separately (e.g. for the assessment of equipment prone to produce interharmonics), all spectral bins resulting from FFT analysis are considered, separately grouped to evaluate signal harmonic and interharmonic content.

The effects of fluctuations of harmonic components, that cause 'sidebands' close to the harmonics, are partially reduced by excluding from interharmonic groups the bins immediately adjacent to the harmonic frequencies.

The interharmonic components $i = 1$ and 9 (50 Hz systems) or 11 (60 Hz systems) directly adjacent to a harmonic are grouped to form a harmonic group according

to (6), whereas the remaining interharmonic components ($i = 2$ to 8 or 10) form the centred interharmonic subgroup according to (7,8).

Fig. 6 gives a clear idea of different bins, grouped to form harmonic and interharmonic subgroups.

Harmonic subgroups for 50 and 60 Hz systems:

$$C^2_{n_{sg}} = \sum_{i=-1}^{+1} c^2_{n \cdot f_0 + \frac{i}{T_w}} \qquad (6)$$

Interharmonic subgroups for 50 Hz systems:

$$C^2_{(n+0.5)_{sg}} = \sum_{i=+2}^{+8} c^2_{n \cdot f_0 + \frac{i}{T_w}} \; , \qquad (7)$$

and for 60 Hz ones:

$$C^2_{(n+0.5)_{sg}} = \sum_{i=+2}^{+10} c^2_{n \cdot f_0 + \frac{i}{T_w}} \; . \qquad (8)$$
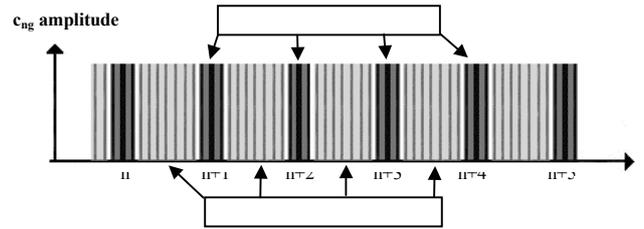

Fig. 6. Illustration of harmonic and interharmonic subgroups
(here represented for a 50Hz system).

3.2. Distortion Factors

In order to perform a voltage or current distortion analysis, the developed instrument evaluates different factors according to [6] and to different standards about emission limits (IEC 61000 Part 3).

The following distortion factors are defined:

- *Total Harmonic Distortion (THD)*
THD is evaluated as the rms value of the harmonics to the rms value of the fundamental; it can be evaluated by using (9) for both 50 and 60 Hz systems.

$$THD = \sqrt{\sum_{n=2}^{40} \left(\frac{c_{n \cdot f_0}}{c_{f_0}} \right)^2} \; . \qquad (9)$$

- *Group Total Harmonic Distortion (THDG)*
THDG is evaluated as the THD but referring to the harmonic groups instead of the central harmonic bin:

$$THDG = \sqrt{\sum_{n=2}^{40} \left(\frac{C_{n_g}}{C_{1_g}} \right)^2} \; , \qquad (10)$$

applicable to both 50 and 60 Hz systems.

- *Sub Group Total Harmonic Distortion (THDS)*

THDS is evaluated as the THDG but referring to the harmonic subgroups. The implemented formula is reported for 50 and for 60 Hz systems in (11).

$$THDS = \sqrt{\sum_{n=2}^{40} \left(\frac{C_{n_{sg}}}{C_{1_{sg}}} \right)^2} \ . \qquad (11)$$

- *Partial Weighted Harmonic Distortion (PWHD)*

This index has been introduced in order to allow the possibility of specifying a single limit for the summation of higher order harmonic signals.

This parameter is evaluated as the ratio of the rms value, weighted with the harmonic order n, of a selected group of higher order harmonics (beginning from the 14th one) to the rms value of the fundamental. Equation (12) allows to obtain PWHD for both 50 and 60 Hz systems.

$$PWHD = \sqrt{\sum_{n=14}^{40} n \cdot \left(\frac{c_{n \cdot f_0}}{c_{f_0}} \right)^2} \ . \qquad (12)$$

3.3. Smoothing

Usually, voltage and current spectral contents vary during monitoring, and, consequently, all groups and subgroups values oscillate. For this reason, in the developed instrument has implemented a smoothing algorithm in accordance with [6,10], based on groups and subgroups values histories.

The developed instrument applies smoothing procedure for both harmonic and interharmonic groups and subgroups and for different distortion factors.

This smoothing is performed over the squared modules C_{ng} of each harmonic order, according to function represented in Fig. 7, corresponding to a first order low-pass filter with a time constant of 1,5 s.
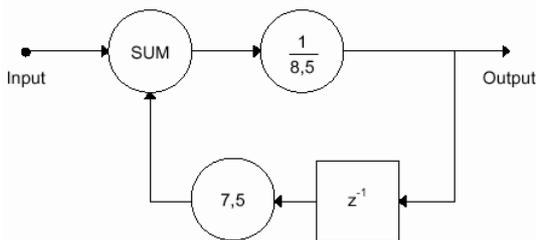

Fig. 7. Low-pass filter: z-1 designates a unit delay.

In order to assure a time smoothed survey of harmonic and interharmonic distortions, instrument provides a further type of post processing applied to the all distortion factors, by averaging 15 contiguous values, updated either every DFT window (every 200 ms) or every 15 time window (every 3 s), depending on the user settings on the control and visualization panel.

For further smoothing evaluations, [6] refers to [10] that defines the generalities about the methods for measurement and interpretation of results for power quality parameters in a.c. power supply systems [10].

This draft standard fixes two different aggregation algorithms categories for the obtained power quality factors:
- cycle integration (fifteen 10/12-cycles intervals respectively for 50/60Hz systems)
- from cycle to time clock integration (10 minutes of 10/12-cycles intervals).

The developed instrument, using the square root of the mean of the squared harmonic and interharmonic subgroups values, performs both of these aggregations.

All smoothed factors are reported in the instrument OUT3 (Fig.2).

4. ACCURACY TESTING

International draft and draft revision standard6 [6-10] and IEEE draft revision guide [11] address two performance classes, depending on instrument accuracy: class I – reference class and Class II – indicator class.

First class is required for instruments used in application where precise measurements are necessary, while, the second one can be used for general surveys, diagnosis and other applications where high accuracy is not necessarily required (measurement far from standard or law limits).

In order to verify the accuracy class (according to the procedure suggested by [6, 10, 11]) for instrumentation measuring harmonic components, the developed system has been tested according to the procedures stated by the same draft standard.

Documents [6,11] define test accuracy procedures for harmonic measuring instruments. The maximum allowable errors are reported in Table 1, and refer to single-frequency and steady-state signals, in the operating range (0-2kHz).

TABLE 1 – Accuracy requirements for current and voltage measurements

I_{nom}: Nominal current range of the measurement instrument
U_{nom}: Nominal voltage range of the measurement instrument
U_m and I_m : Measured values

Class	Measurement	Conditions	Maximum Error
I	Voltage	$U_m \geq 1\% \ U_{nom}$ $U_m < 1\% \ U_{nom}$	$5\% \ U_m$ $0,05\% \ U_{nom}$
	Current	$I_m \geq 3\% \ I_{nom}$ $I_m < 3\% \ I_{nom}$	$\pm 5\% \ I_m$ $\pm 0,15\% \ I_{nom}$
II	Voltage	$U_m \geq 3\% \ U_{nom}$ $U_m < 3\% \ U_{nom}$	$5\% \ U_m$ $0,15\% \ U_m$
	Current	$I_m \geq 10\% \ U_{nom}$ $I_m < 10\% \ U_{nom}$	$\pm 5\% \ I_m$ $\pm 0,5\% \ I_{nom}$

The instrument has been set to 4096 signal points sampled by means of a 12 bit DAQ board.

Naturally, when frequency component is inside the band [47,5 - 52,5] Hz, instrument perform a synchronous sampling, while, outside this range, instrument needs a reference frequency to perform sampling frequency evaluation.

In order to test instrument accuracy also in unsynchronous sampling conditions, different measurements have been carried out with different monotonal signals with harmonic order *n*=1,10,20,30,40. For any *n*≠1, sampling

reference frequency has been fixed to 47,5 Hz, 50,0 Hz and 52,5 Hz. Of course, when no synchronous condition is detected, signal sampled buffer is windowed (Hanning function) before processing FFT.

Moreover, tests have been conduced for signal amplitudes equal to 0,1%, 0,5%, 0,9%, 1%, 20%, 60% and 100%U_n.

Test signals have been generated with a 16 bit board and this output has been analysed by means of a digital multimeter HP34401A with an accuracy of (1%rdg+0,04% rng). Moreover, multimeter has been used to verify the compatibility of its accuracy band with the instrument one.

Experimental results show errors drastically below standard limits when signal is synchronously sampled maximum (error 0,12%U_m for $U_m \geq 1\%U_{nom}$ and 0,019%U_{nom} for $U_{m<}1\%U_{nom}$); when instrument looses synchronous condition, maximum obtained error is about 1%U_m for $U_m \geq 1\%U_{nom}$ and 0,028%U_{nom} for $U_{m<}1\%U_{nom}$.

Therefore, the instrument can be considered as a reference class one, also when it is coupled with a commonly used voltage or current transducer.

5. CONCLUSIONS

In this paper, a new computer based instrument for harmonics and interharmonics measurement is presented. The developed system deals with all in force and draft standards about power quality measurement methods and harmonic and interharmonic analysis, and about emission limits (IEC 61000 part 3).

Synchronization has been performed by means of a Chirp Z Transform based synchronizer developed by Authors, presented in a previous work and briefly summarized, that deals with standard limits also in presence of interharmonic current or voltage distortion (instrument synchronization and setting panel is reported in Fig.8).

Instrument outputs allow to give a complete distortion analysis and monitoring of power supply and equipment connected thereto.

The control and visualization panel (Fig. 9) reports harmonics and interharmonics spectral components, groups, subgroups, distortion factors and their averaged and smoothed values as required by previous mentioned international in force or draft documents, and a complete visualization of these values time histories.From the setting panel, users can easily set the instrument both for 50 and for 60 Hz systems without any additional variation of its algorithm.

The instrument has been characterized as required by [6,10] to evaluate its accuracy class.

The result is that proposed and developed instrument can be used, according to [6] where precise measurements are necessary, such as for verifying compliance with standards, resolving disputes, or for emission measurements, if the emissions are near to the limit values.

Developed harmonic and interharmonic measurement system can be easily implemented on any microprocessor system. Moreover, evaluation time required by the instrument to perform all computations is lower than observation window (10-12 fundamental cycles). This allows to obtain a complete on-line distortion survey of power systems and equipments connected thereto with low memory requirement.

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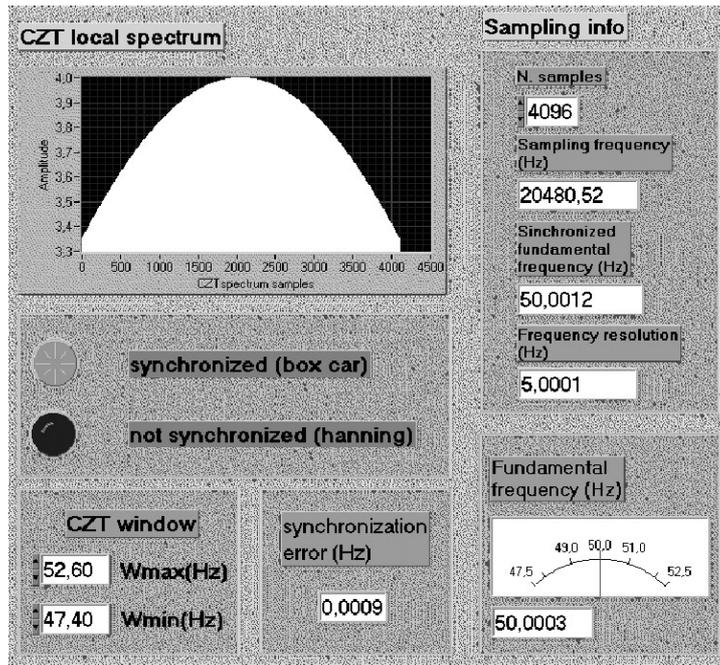
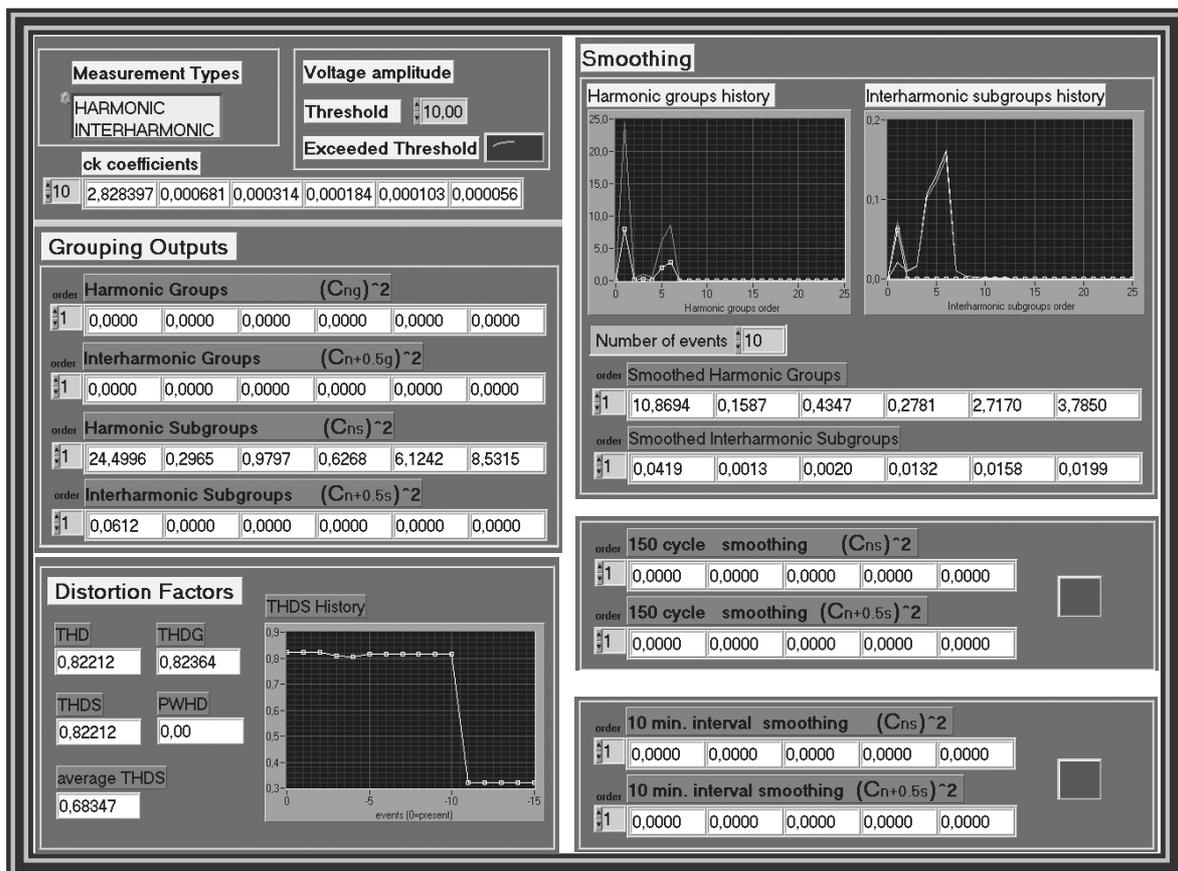Fig. 8. Instrument synchronization and setting panel.

Fig. 9. Instrument front panel for control and visualization.

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