Real-Time Interharmonics Detection and Measurement Based on FFT Algorithm

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***Abstract*-The modern power systems are supplying an increasing number of non-linear loads like: double conversion systems, arc furnaces, arc discharging, high power Cycloconverter (CCV) etc. These loads are harmonics and interharmonics sources. Therefore, it is important to measure interharmonics accurately. The Fast Fourier Transform (FFT) is used for signal processing because of its computational efficiency. Most power quality meters and digital relays adopt FFT-Based algorithm to characterize harmonics of the measured signals. The International Electrotechnical Commission (IEC) standards on power quality have defined the terminology, limits and measurements guidelines for interharmonics. This paper shows effects on windowing in the interharmonics detection based on IEC technique. Simulations and experimental results based on the Real-time platforms are discussed.**

I. INTRODUCTION

The fast growing of the power electronics systems and periodical time-varying loads in electric power system has led to severe harmonic and interharmonic distortion. IEC-61000-2-1 [1] defines the interharmonics as follows: "Between the harmonics of the power frequency voltage and current, further frequencies can be observed which are not an integer of the fundamental. They can appear as discrete frequencies or as a wideband spectrum." Table I provides a simple, yet effective mathematical definition.

The Fast Fourier Transform (FFT) is the most commonly used technique for harmonic spectral analysis. Most power quality meters and digital relays adopt FFT-Based algorithm to characterize harmonics of the measured signals. When both the interharmonics and harmonics are present into the power system, the direct applications of FFT for spectral analysis many lead to inaccuracies due to leakage and the picket-fence effects. The IEC standard draft 61000-4-30 and 61000-4-7 [2], [3] contain methods of measurement and interpretation of results for harmonic and interharmonics distortion.

They are synthesized with reference to 50-Hz systems and, then, referred to as "IEC technique" which the window width must be exactly ten periods of the fundamental period, corresponding approximately to 200 ms with 5Hz of frequency resolution. The measurement and analysis experiences have shown that great difficulties arise in the interharmonics detection and measurement on the power systems as high power cycloconverter (CCV) [4], based on the FFT algorithm with acceptable levels of accuracy [5]-[6] due to the leakage problem. Several studies applying complex windows have been performed for the Interharmonics detection [7]-[8]. A detailed harmonic analysis for different windows to two-tone signals [9] demonstrates the influence of a window exerts on the detection of a weak spectral line in the presence of a strong nearby line. This paper shows a review to the harmonics and interharmonics analysis based on IEC technique using the Rectangle and Hanning windows. Simulations and experimental results using real-time platforms, for a synchronized analysis between the sampled data (i.e. N) and the sampling frequency (i.e. f_S) for a proper frequency resolution on the FFT are presented.

TABLE I
MATHEMATICAL DEFINITIONS OF INTERHARMONIC

Item	Definition
Harmonic	$f = h * f_1$, where h is an integer > 0
DC	$f = 0$ Hz ($f = h * f_1$, where $h = 0$)
Interharmonic	$f \neq h * f_1$, where h is an integer > 0
Sub-harmonic	$0 < f < f_1$

* where f_1 is the fundamental power system frequency

II. MATHEMATICS BASIS

If $x(t)$ is a continues periodical signal with period T and it satisfies Dirichlet conditions, one can represent it by Fourier series of

$$x(t) = \sum_{k=-\infty}^{\infty} X(k\Omega_0) e^{j\Omega_0 t} \tag{1}$$

where $\Omega_0 = 2\pi/T$ is called fundamental angular frequency and $X(k\Omega_0)$ is the Fourier coefficient at the *k*th harmonic. This implies that a non-sinusoidal periodical signal can be separated into a series of sinusoidal components with frequencies, which are integer multiples of the fundamental frequency. In order to implement Fourier analysis in computer, the signal in both time and frequency is discrete and has finite length. Discrete Fourier Transform (DFT) is then introduced. Assume that $x(t)$ is sampled with a rate of N point per cycle, i.e., $T_S = T / N$.

The corresponding DFT will be

$$X(w_k) = \sum_{n=0}^{N-1} x(n) e^{-j(2\pi/N)nk} \quad (2)$$

$$k = 0,1,...., N-1$$

where $w_k = (2\pi/T_S N\ k) = (2\pi/T)k$, $X(w_k)$ is the so-called spectrum of $x(n)$. Here $x(n)$ is assumed to be one cycle of a periodical signal. The angular frequency resolution of the spectrum is determined by the length of the signal as $\Delta w = 2\pi/T$. Thus, if T is selected as one period of $x(n)$, the outcomes spectrum will be only show components that are integer multiples of the fundamental frequency, which are defined as ***Harmonics***. However, if the data length is selected as $p1$ cycles ($p1 > 1$ and is an integer) of the fundamental, the frequency resolution will change as $\Delta w = 2\pi/p1 \quad T = w_1/p1$. These non-integer order components, according to IEC definition, are called ***Interharmonics.***

III. IEC STANDARD 61000-4-7

The IEC standard draft 61000-4-7 and 61000-4-30 contain methods of measurement and interpretation of results for harmonics and interharmonics distortion. For the assessment of harmonics the output of the DFT is first grouped to be the sum of the square intermediate lines between two adjacent harmonics according to equation (3) (Fig. 1). The resulting harmonic group of the order n (corresponding to the center line in the hatched area) has the magnitude $G_{g,n}$ (rms value).

$$G_{g,n}^2 = \frac{C_{k=5}^2}{2} + \sum_{i=-4}^{4} C_{k+1}^2 + \frac{C_{k+5}^2}{2} \quad \{50\text{ Hz}\} \quad (3)$$

Where C_{k+i} is the rms value of the spectral component corresponding to an output bin (spectral line) of the DFT, and $G_{g,n}$ is the resulting r.m.s. Value of the harmonic group.

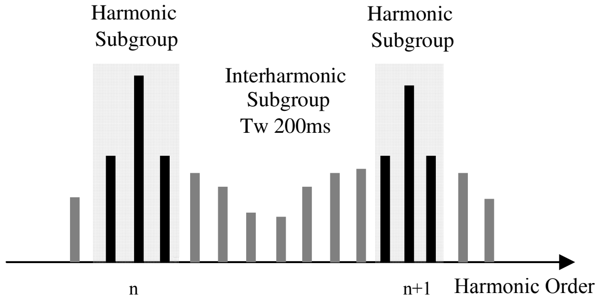

Fig. 1. IEC grouping of spectral components for harmonics and interharmonics.

The harmonic order n is equal to k/N , with k the number of the Fourier component and N the number of periods in the time window (N=10 in a 50 Hz system). The harmonic subgroup, as defined in the standard, is obtained using the output components C_k for each 5 Hz of the DFT grouped according to equation (4).

$$G_{s,g}^2 = \sum_{i=-1}^{1} C_{k+i}^2 \quad (4)$$

where $G_{sg,n}^2$ is the harmonic subgroup pf order n.

The interharmonic group is defined in the standard as the r.m.s value of the all interharmonic components in the interval between two consecutive harmonic frequencies. This grouping provides an overall value for the interharmonic component which includes the effects of fluctuations of harmonic components. Equation (5) permits the calculation of the value of the interharmonic group:

$$C_{ig,n}^2 = \sum_{i=-1}^{9} C_{k+i}^2 \quad \{50\text{ Hz power system}\} \quad (5)$$

$C_{ig,n}^2$ is the interharmonic group of order n, which corresponds to the interharmonic group between the harmonic order n and n+1. The frequency of the interharmonic group is defined as the mean of the two harmonic frequencies between the group is situated.

$$C_{isg,n}^2 = \sum_{i=-1}^{8} C_{k+i}^2 \quad \{50\text{ Hz power system}\} \quad (6)$$

$C_{isg,n}$ is the r.m.s value of the interharmonic centered subgroup of order n and corresponds to the interharmonic subgroup between harmonics of order n and $n+1$. The frequency of the interharmonic centered subgroup is also defined as the mean of the two harmonic frequencies between which the subgroup is situated.

IV. ON THE USE OF WINDOWS

The process to limit the time to a signal is known as windowing which introduces errors in the frequency spectrum of the signal. Only in the case of an exact synchronization between the observation time and the period of the signal, there is no truncation error at the end of the window so that the spectrum of the signal is correct. For any other frequency component of the signal not periodic with the observation time will present an uncertainty in the determination of the component due to the loss of continuity at the boundaries of the window. The error introduced is known as *spectral leakage*.

In the analysis of real power system waveform, spectral leakage problems originate from two main causes:

i) the error in synchronizing fundamental and harmonics, that is the difference between the actual value an the value utilized to calculate T_W for the signal processing;

ii) the presence of interharmonics nonsynchronized with DFT bins

The classical approach to reduce the effect of the spectral leakage associated with finite observation intervals is the use of window functions. The objective when choosing a window function is to obtain the best frequency resolution and the least contribution from interfering spectral components. Two windows more commonly used in the harmonic measurement instruments are *Rectangular* and *Hanning* window. Fig 2 shows the continuous spectrum for the both Rectangular and Hanning windows. Hanning weighting is only allowed in the case of loss of synchronization. Fig.3 shows the harmonic spectrum using the IEC technique for a test signal, as given in (7), where the measured signal contains both harmonics and interharmonics.

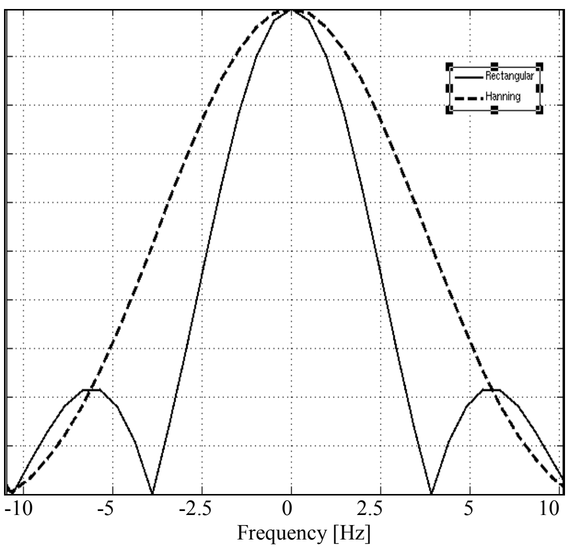

Fig. 2. Continuous spectrum of Rectangular and Hanning windows and DFT components

$$\begin{aligned} v(t) &= 5\sin(f \times 2\pi t) + 1.5\sin(3f \times 2\pi t) \\ &+ 0.75\sin(7f \times 2\pi t) + 0.5\sin(310 \times 2\pi t) \\ &+ 0.5\sin(686 \times 2\pi t) + 0.5\sin(952 \times 2\pi t) \\ &where \quad f = 50.1Hz \end{aligned} \quad (7)$$

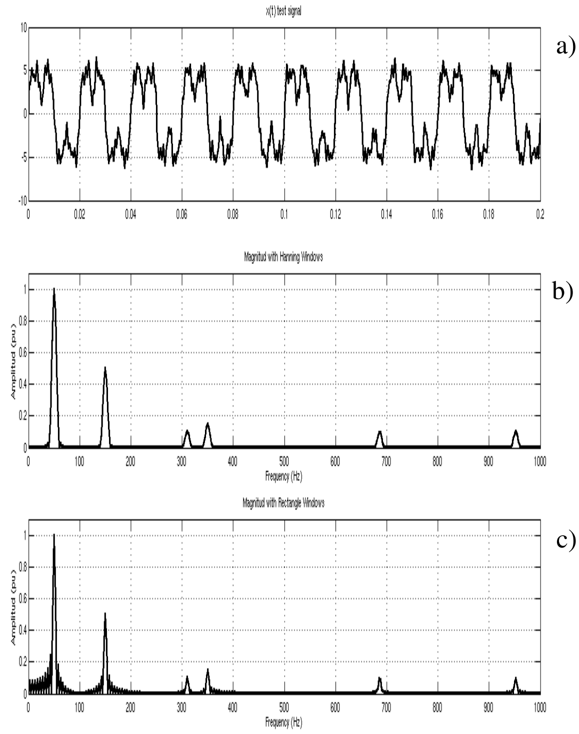

Fig. 3. Harmonic spectrum obtained for the a) test signal using b) Hanning and c) Rectangular windows

The test signal (7) analyzed above in MATLAB, has an ideal synchronization between the fundamental period of the signal f and the window width. The sampling frequency used and sampled data is $f_S = 10kHz$ and N=2000 respectively. On the other hand, when applying FFT for the sampled signal, the harmonic spectrum can not be properly expressed if the harmonic frequency is not an integer multiple of frequency resolution. This problem leads to the actual harmonic component appearing closest scale of the harmonic frequency, which is referenced as the *picket-fence effect*.

V. IEC TECHNIQUE IMPROVEMENTS

The harmonics and interharmonics analysis based on the IEC technique is used to one time width around 200ms and 10 cycles of the fundamental frequency. In order to compare different signal processing techniques on field analysis and measurements, the authors propose a modified IEC technique based on the following premise: to have 1 Hz of frequency resolution ($i.e. f_r = 1$), with the number of sampled data ($i.e. N$) equals sampling frequency ($i.e. f_S$). To demonstrate this particular case, the test signal will be modified by considering the presence of a strong nearby frequency around 53 Hz. Fig 4 and 5 show signal spectrum for two cases using the Hanning and Rectangular window with 4096 (10 cycles) and 4096 (25 Cycles) points to be evaluated on FFT algorithm and synchronized with the time width of the sampling signal.

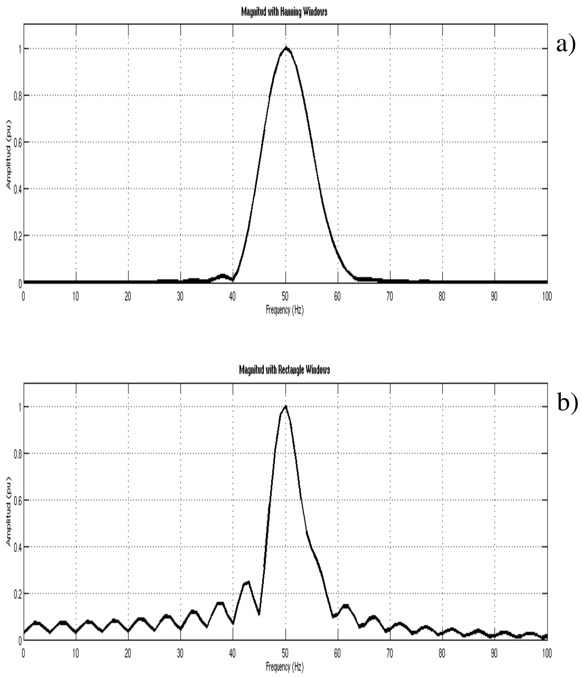

Fig. 4. FFT synchronized with N=4096 for a) Hanning and b) Rectangular window using the IEC Technique.

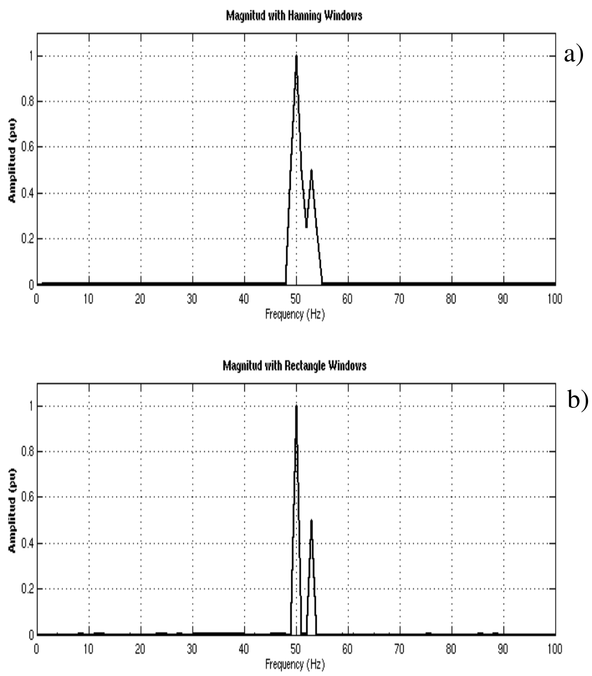

Fig. 5. FFT synchronized with N=4096 for a) Hanning and b) Rectangular window using a resolution frequency equals to 1 Hz

Clearly, when using the rectangular window, it gives a spectrum resolution for detecting a nearby interharmonic more accurate that hanning window. Obviously, the Number of Cycles increases as N grows. Experimental results using a DAQ with LabView platform are possible of implementing with a high precision algorithm for this purpose.

VI. EXPERIMENTAL RESULTS

To illustrate the simulations obtained in MATLAB for measuring harmonics and interharmonics, the measuring system over LabView and TMS320C2000 ControlSTICK PICCOLO^{TM} are implemented and tested.

A. Using the LabView Platform

A LabView-based lab test setup is used for implementing IEC Technique. The test signal, as given in (7), is virtually generated and sampled using a DAQCard-6036 through of an ADC and is modified so that, the measured signal contains nearby interharmonics to the fundamental frequency (*fih*=53Hz).

According to the IEC Technique, with the resolution frequency equals 5 Hz, this interharmonic is impossible to detect due to picket-fence effects around 50 Hz. Fig. 6 shows the harmonic spectrum obtained for the test signal. A projection of the first two harmonics and an interharmonic (picket effect) at 55 Hz also is possible to observe in this figure.

It is import to mention that when the size of the input sequence is not a power of two but is factorable as the product of small prime numbers, the FFT-based VIs use a mixed radix Cooley-Tukey algorithm to efficiently compute the DFT of the input sequence.

When using the IEC Technique the Total Distortion Harmonic obtained is around THD=38%.

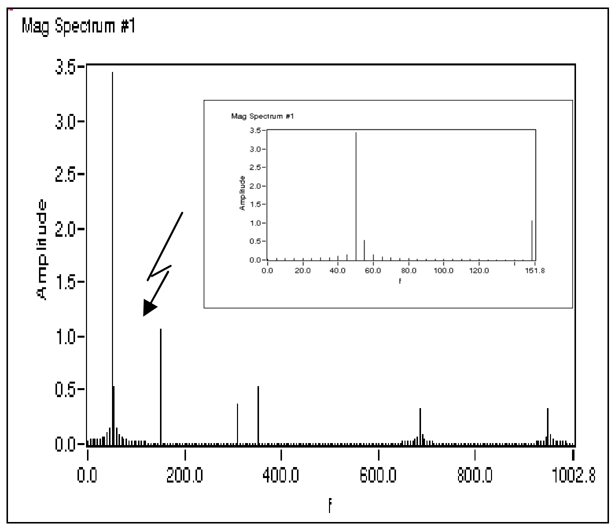

Fig. 6. Harmonic spectrum obtained with a) *fs*=10kS/s and *N*=5000 based on the IEC Technique bin=5Hz

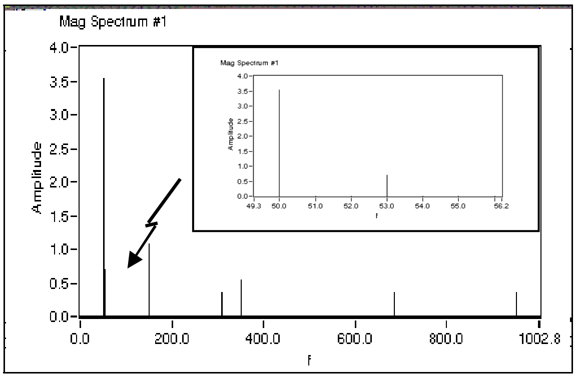

Fig. 7. Harmonic spectrum obtained with fs=4.10 kS/s and N=4096 based on modified IEC Technique bin=1Hz.

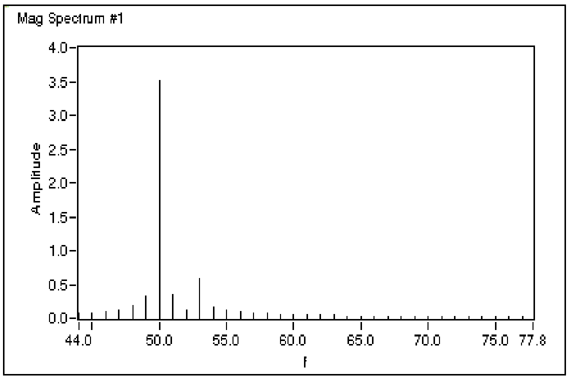

Fig. 8. Harmonic spectrum obtained with a deviation of the fundamental frequency value to 50.1 Hz.

Fig. 7 shows the same frequency spectrum using the modified IEC technique with sampling frequency equals sampled data. In this case, the Total Harmonic Distortion is around THD=35%. As indicated in Table II, it is found that the Modified IEC Technique is very accurate in determining the fundamental amplitudes of the signal test.

A sensitivity analysis simple for deviations of the fundamental frequency value is applied to the modified IEC technique. According to IEC standard for class 'A' instruments, ± 10 mHz are allowed. Fig. 8. shows a test simple for a variation of ± 100 mHz where the sampled data must be increased or decreased around ± 16 samples respectively to correct the picket-fence effect due to frequency shift.

TABLE II
COMPARISON BETWEEN CONVENTIONAL FFT, STANDARD AND MODIFIED IEC TECHNIQUE

Simulated Test Signal		FFT	Standard IEC Technique	Modified IEC Technique
Freq. (Hz)	Ampl. (V)	Ampl. (V)	Ampl. (V)	Ampl.(V)
50	5	3.53	3.40	3.53
53	1	0.70	0.527	0.70
150	1.5	1.06	1.02	1.06
350	0.75	0.53	0.52	0.53
310	0.5	0.35	0.34	0.35
686	0.5	0.35	0.33	0.35
952	0.5	0.35	0.33	0.35

B. Using a TMS320C2000 ControlSTICK PICCOLO™

The ControlSTICK PICCOLO™ [10] is the latest real-time microcontroller platform chosen to implement an interharmonics measurement and detection with a low-cost evaluation tool. The F2802x Piccolo™ family of microcontrollers provides the power of the C28x™ core coupled with highly integrated control peripherals in low pin-count devices. Fig 9 shows a picture of the evaluation tool used to implement the interharmonics measuring system. Fig 10 shows the implemented algorithm diagram for measuring the harmonics and interharmonics on the DSP platform.

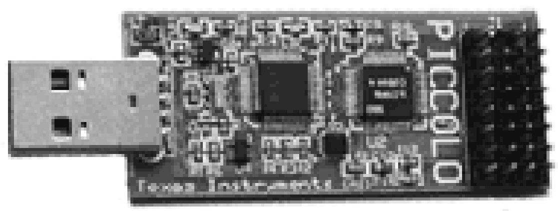

Fig. 9. TMS320C2000 ControlSTICK PICCOLO™

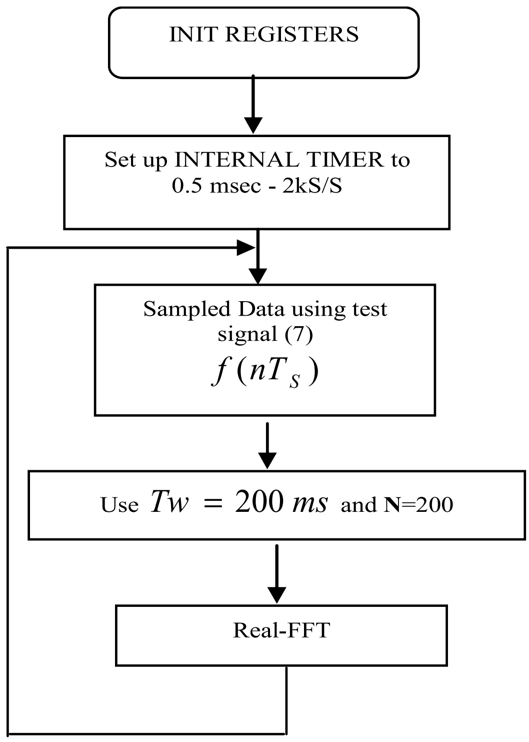

Fig. 10. Algorithm implemented for Interharmonics spectrum measuring.

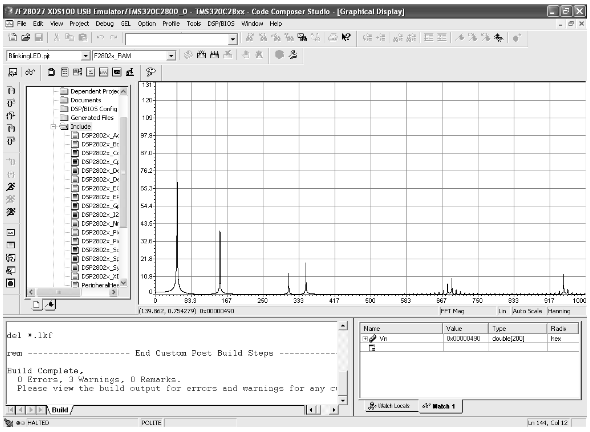

Fig. 11. Harmonic spectrum obtained using the test signal (7) on the CCStudio V3.3 using the IEC technique and Hanning window.

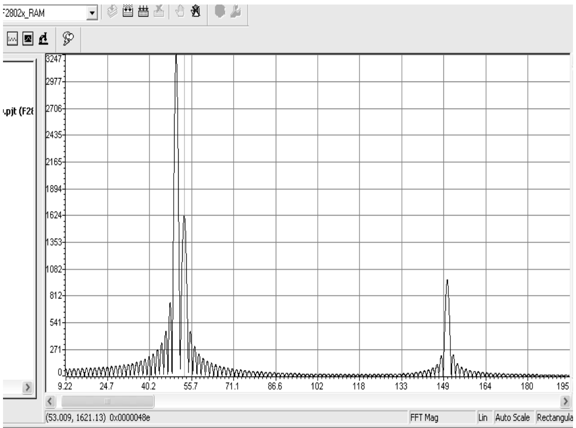

Fig. 12. A detail for the harmonic spectrum obtained using the modified test signal with an interharmonic in 53Hz. The IEC technique modified, Rectangular window and N=4096.

The test signal is internally generated using a precision timer. By using the signal processing library, the Real-FFT is implemented and plotting on the real-time mode. Fig. 11 shows the harmonics and interharmonic spectrum obtained after Real-FFT applying the test signal using the Hanning window.

A modified IEC technique, i.e. by using a time width equals 4 sec; a more precise resolution spectrum allows detection for nearby interharmonics (53 Hz) to the fundamental frequency. For this case the Real-FFT is calculated using N=4096 samples. Fig. 12 shows a zoom of the fundamental frequency, interharmonic and 3rd harmonic.

VII. CONCLUSIONS

In this paper, a review to the interharmonics detection and measurement based on the Fast Fourier Transform has been described. To illustrate the behavior of the frequency spectrum based on Hanning and Rectangular window, simulation results using the IEC technique and ideal resolution frequency are presented. It is shown that for real-time LabView-based measurements, more accurate results for interharmonics detection are obtained. By using the DSP evaluation tool, both the IEC technique and modified IEC are successfully implemented and a low-cost measuring instrument is possible to be built using this PICCOLO™ development platform.

The authors aim to achieve a real-time industrial monitoring for power quality and diagnostics assessment using a DSP-wireless sensor platform.

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