

# INTER-HARMONIC DETECTION AND ESTIMATION IN LOW-FREQUENCY CONDUCTED ELECTROMAGNETIC INTERFERENCE MEASUREMENTS

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*Abstract: The IEC 1000-4-7 standard is currently mandated to fix both procedures and instruments for evaluating the level of harmonics and inter-harmonics in electromagnetic interference measurements for power supply systems and connected equipment. Prescriptions and recommendations related to inter-harmonics seem to be not well detailed; this is particularly true for those showing a non-stationary behaviour. As a matter of fact, only a digital signal-processing approach, based on the Discrete Fourier Transform, is strongly recommended; little or nothing is said both about the sampling rate to be adopted and the time window to be observed.*

*The paper aims at designing suitable measurement procedures based on advanced digital signal-processing algorithms in order to overcome the aforementioned limits. In particular, to allow non-stationary inter-harmonics to be monitored and properly analysed, a new approach, based on the use of Time-Frequency Representations, improved by a recently introduced reassignment technique, is proposed.*

*After a detailed description of the proposed approach, its efficiency and suitability is assessed by means of tests on numerical signals as well as on actual signals directly acquired on the field.*

*Keywords: Inter-harmonic measurements, EMI measurements, EMC standards*

## 1 INTRODUCTION

The wide diffusion of motor drives and converters, developed into the megawatt range, resulted in an increasing interest about the measurement of electromagnetic interference (EMI) produced in power systems. This kind of produced EMI turns into the generation of undesired inter-harmonics, that is of non-harmonic signal components, the frequencies of which are related to the system fundamental frequency by rational fractions [1,2].

These undesired components found in the mains spectrum are, for example, originated anytime two AC power systems, fed at different frequencies, are joined together via a DC link which is not able to completely decouple them. Thus, the inter-harmonics can be thought of as the result of an inter-modulation process between the current (in terms both of fundamental and harmonic components) flowing in a power system and the current flowing in the other.

Inter-harmonics can also arise from a number of other different reasons such as periodically time varying loads, circuits with multiple switching functions (step-down converters), deviations of the fundamental frequency from its nominal value, and so on.

Anyway, regardless their origin, the great interest in detecting and measuring inter-harmonics is strongly justified by the importance of their undesired effects such as malfunctioning of remote control system, erroneous firing of thyristor apparatus, display or monitor image fluctuations, lighting system flicker [3,4,5], and so forth.

## 2 INTER-HARMONIC MEASUREMENT: STATE OF ART VERSUS A NEW PROPOSAL

Inter-harmonic presence can easily be evidenced by a quick test based on the direct monitoring of the current waveform through an oscilloscope as the showing of a characteristic ripple on the top of the

current pulses. Much more difficult is, instead, the precise assessment of inter-harmonic level and frequency.

At this concern, the IEC 1000-4-7 standard is currently mandated to fix both procedures and instruments for measuring harmonics and inter-harmonics [6]. With regard to inter-harmonic measurement, a distinction is made between recommendations to be applied to (quasi-) stationary inter-harmonics and those for rapidly floating (or non-stationary) ones. At a closer look, these recommendations seem to be not sufficiently detailed for practical applications; even more crucial is surely the non-stationary case due to amplitude and/or frequency variations versus time. Specifically, the aforementioned standard strongly recommends to treat non-stationary inter-harmonics by using a digital signal-processing approach, based on the *Discrete Fourier Transform* (DFT). But, little or nothing is said about both the sampling rate ( $f_s$ ) to be used and the time window ( $T_w$ ) to be observed. The value given for  $T_w$  (0.16 s) is only related to interference measurements regarding ripple control receivers and is highlighted as a "good trade-off" between frequency resolution and time resolution.

Beside IEC 1000-4-7 standard, some different approaches have recently been proposed in literature for measuring inter-harmonics. Among them, one suggests to use a special algorithm, the "zoom FFT" algorithm, to gain the necessary frequency resolution: a classical FFT is preliminarily executed on the signal under test with the aim of highlighting eventual spectral lines at non-harmonic frequencies. Then, any frequency range, which seemed to contain an inter-harmonic, is more accurately scanned (*zoomed*) by using a Chirp Z Transform (CZT) capable of granting high resolution as well as good accuracy in frequency measurement. Both amplitude and phase of the inter-harmonic are finally derived from the results of a DFT synchronised with the previously measured frequency [7]. Due to the adopted solutions, this technique cannot work well in the presence of non-stationary inter-harmonics.

The present paper mainly aims at designing a new digital signal-processing based procedure for non-stationary inter-harmonic detection and measurement thus removing the hypothesis of stationary system. The fundamental stages of the implemented procedure can be summarised as follows: (i) the acquired signal is first wiped both from the fundamental and its eventual harmonics; (ii) a time-frequency representation (TFR), applied to the filtered signal, provides smear evolutions versus time both of frequency and magnitude of its inter-harmonics, which are best focused by a successive reassignment of TFR results; (iii) a peak location process conducted on these reassigned results gives the actual traces versus time of inter-harmonics' frequency and magnitude; (iv) the removal of noise eventually produced by the reassignment is numerically accomplished by low-pass digital filtering.

To put on view problems related to digital signal-processing and clearly explain the reasons behind the choices made, the results of tests carried out on simulated signals are first shown and discussed. Results obtained from the application of the proposed procedure to actual signals acquired on the field are given later.

### 3 TESTS ON SIMULATED SIGNALS

The first test here presented refers to a sine-wave signal corrupted by an inter-harmonic, constant in magnitude but non-stationary in frequency. To this aim, on the fundamental (50Hz sine-wave)

$$y_0(t) = \sin(2\pi \cdot 50 \cdot t)$$

the non-stationary inter-harmonic, expressed by the signal

$$y_1(t) = 0.02 \cdot \sin(j(t))$$

is superimposed. The function  $j(t)$  describing the frequency variation is linear and spans between 200 and 250 Hz in a time interval of 0.4 s. Furthermore, to highlight sensitivity problems, the magnitude of the superimposed signal is chosen to be only 2% of that of the fundamental sine-wave.

Due to these choices, the time-domain representation of the simulated signal, shown in Fig. 1a, seems to be a sine-wave. The frequency representation, obtained with a traditional FFT

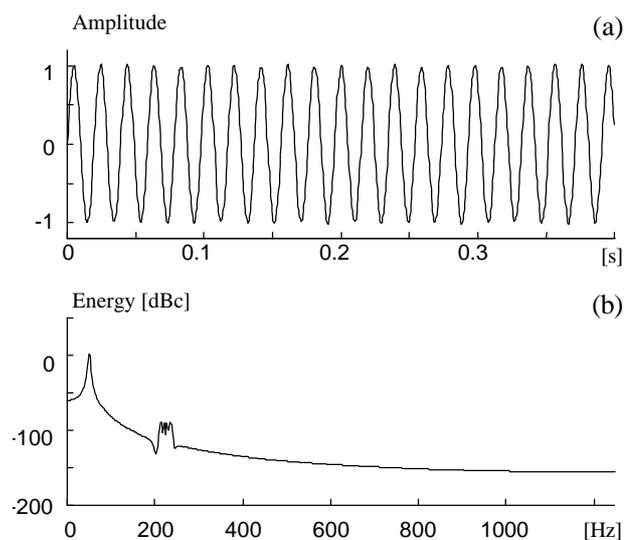
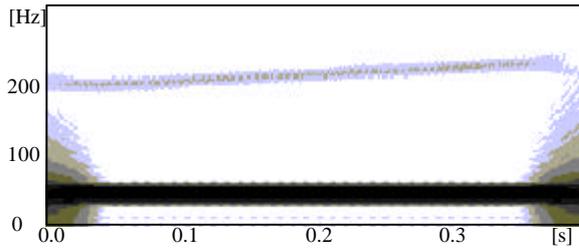
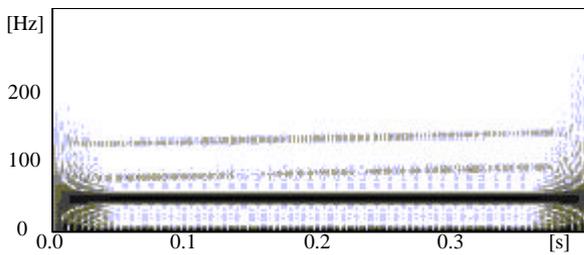


Figure 1. Time (a) and frequency (b) representations of the simulated signal.

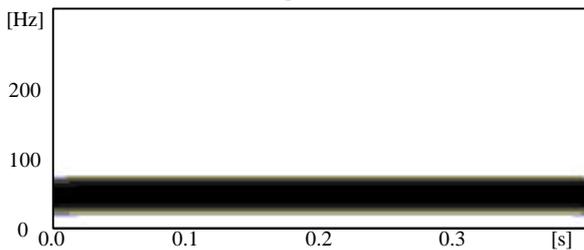


**Figure 2.** Results of the STFT applied to the simulated signal.

common, linear TFR, applied to the considered signal are shown in Fig. 2. In particular, time is reported on the horizontal axis, frequency on the vertical one and amplitudes are represented by a grey scale (clipped to  $-300$  dBc). It is worth noting that much more information is available with respect to the previous case. It is possible to observe the 50 Hz fundamental with a superimposed signal the frequency of which spans linearly in the chosen time window (0.4 s) from 200 up to 250 Hz. Anyway,



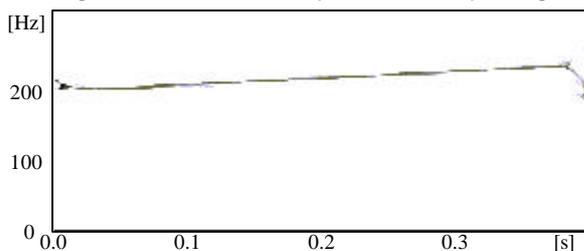
**Figure 3.** Results of the WVD applied to the simulated signal



**Figure 4.** Results of smoothed WVD applied to the simulated signal.

Results obtained from the application of the *Wigner-Ville Distribution* (WVD) to the same signal are given in Fig. 3. As shown in Appendix, quadratic TFRs introduce typical artefacts caused by cross-components, the amplitudes of which are strongly related to those of components themselves. This is the reason why, in the considered example, the magnitude of the fundamental (50 times greater than that of the inter-harmonic) produces cross-components that completely mask the inter-harmonic to be measured. The smoothed version of the WVD has then been applied to reduce the effect of cross-components. The achieved results, given in Fig. 4, show that cross-components have strongly been mitigated. However, a new undesired effect appears: attenuation and focus loss caused by energy spreading along the spectrum. Because of its high magnitude, the fundamental remains still evident in the smoothed representation even though attenuated and less focused. Conversely, the inter-harmonic, being both much lower in magnitude than the fundamental and attenuated and unfocused in the same percentage, results to be too small to be successfully detected.

To overcome this limitation, a filtering stage is carried out. In particular, a notch-filter is adopted for abating fundamental's amplitude thus putting in more evidence the inter-harmonic to be measured.



**Figure 5.** Results of reassigned, smoothed WVD applied to the simulated signal after fundamental filtering.

algorithm (Fig. 1b) highlights, beside the fundamental at 50 Hz, the presence of some energy spent between the fourth and the fifth harmonic (from 200 up to 250Hz). However, as expected, no information is given about time intervals during which this energy is spent. Hence, a different measurement procedure must be used if time-frequency correlation is required. The solution is found in the so called TFR algorithms (see Appendix).

As an example, the results provided by the *Short Time Fourier Transform* (STFT), a very common, linear TFR, applied to the considered signal are shown in Fig. 2. In particular, time is reported on the horizontal axis, frequency on the vertical one and amplitudes are represented by a grey scale (clipped to  $-300$  dBc). It is worth noting that much more information is available with respect to the previous case. It is possible to observe the 50 Hz fundamental with a superimposed signal the frequency of which spans linearly in the chosen time window (0.4 s) from 200 up to 250 Hz. Anyway, also the STFT shows some drawbacks: firstly, amplitudes are still poorly meaningful and, secondly, frequency variations are still poorly resolved. In particular, if a more complex signal is considered, including, for example, two inter-harmonics with frequencies very close to each other, they could erroneously appear as overlapped. In this case, a better digital signal-processing choice would surely be the use of quadratic TFRs (see Appendix).

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To overcome this limitation, a filtering stage is carried out. In particular, a notch-filter is adopted for abating fundamental's amplitude thus putting in more evidence the inter-harmonic to be measured. TFR results are focused by means of a reassignment technique, details of which are given in Appendix. The evolution of inter-harmonic's frequency versus time is thus made clear with success (Fig. 5): the fundamental is disappeared from the representation, the artefact due to cross-components is completely absent, the inter-harmonic is highlighted and suitably focused for allowing a good measurement quality.

The successive stage of the measurement procedure is the explicit evaluation of the function,  $f(t)$ , describing the evolution of inter-harmonic's

frequency versus time. A suitably implemented algorithm locates, for each instant of time, the peak value of the reassigned TFR, evaluates the corresponding frequency value given on the vertical axis, and finally assigns it to the considered instant of time. At the end, to increase the signal-to-noise ratio, the resulted signal,  $f(t)$ , is low-pass filtered. The function  $f(t)$  is shown in before (Fig. 6a) and after (Fig. 6b) low-pass filtering process along with its nominal evolution (the straight line between 200 and 250 Hz), assumed as reference. If boundary effects are neglected, the measurement result in a whole seems to be very satisfactory.

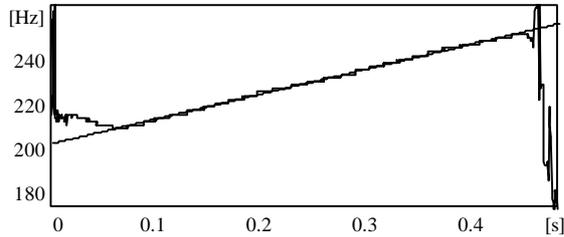


Figure 6. a) Inter-harmonic frequency variation versus time

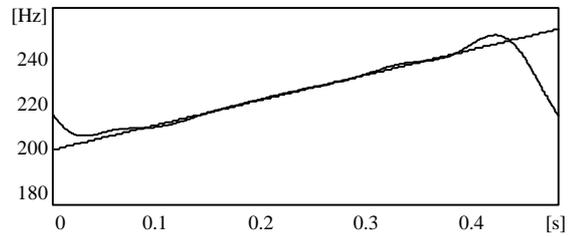


Figure 6. b) Smoothed inter-harmonic frequency variation versus time

A similar algorithm has been used also for evaluating the evolution of inter-harmonic's magnitude versus time. Figs. 7 a, b show how accurately the constant magnitude (only 0.02 times fundamental's magnitude) is measured.

Furthermore, other tests have been carried out on simulated signals in order to find out most of the potentialities the proposed measurement procedure can offer. According to the obtained results, it is

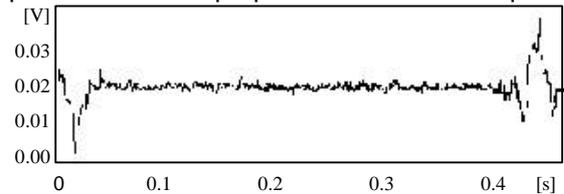


Figure 7. a) Inter-harmonic magnitude

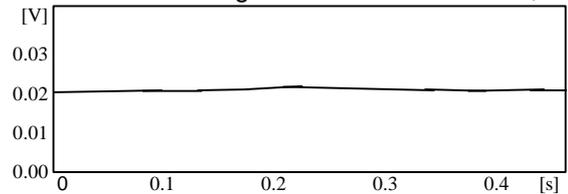


Figure 7. b) Smoothed inter-harmonic magnitude

worth noting that this procedure is capable of measuring either frequency or magnitude evolutions versus time of inter-harmonics with a satisfactory accuracy (relative differences between measured traces and nominal ones within few percents). However, accuracy degrades if both frequency and magnitude of inter-harmonics vary at the same time. This is the reason why the study is still in progress, and much attention is paid both to overcome the aforementioned problem and exhaustively assess the performance of the procedure.

#### 4 INTER-HARMONICS MEASURED ON AN ACTUAL POWER PLANT

To highlight the nice functioning as well as potentialities granted by the proposed procedure when applied also to actual data, the results obtained on the static starting-up system of the power hydro-electric pumped-storage of Presenzano (Italy) are given and analysed.

At this concern, the Presenzano power plant is composed by four 250 MW generation units, for a total of 1000 MW [8]. During day hours, the high power demand is supplied by the units working in the generating state by using the water stored into an upper basin. During night, when power demand is much lower, the units pump the water from a lower basin to the upper one. A static converter, based on a traditional thyristor scheme, is used for starting-up the units, one at a time, for launching pumping stages. At first, a couple of inverter's thyristors, depending on rotor's position, is fired. The rotor moves and, when 60 electrical degrees have been slip away, the thyristor couple is turned-off, a proper phasing back time is waited for and then the next couple is fired. The so working switching process introduces high level ripple voltages into the inverter dc link which, in turns, produce spurious harmonics associated with the output frequency. As the dc link current is reflected back into the ac power supply, an inter-modulation process takes place and hazardous inter-harmonics are consequently generated. Hence, from the plant management point of view, great interest is devoted to the measurement of inter-harmonics originated during the start-up phase.

To this aim, the transient current flowing into the dc link during the aforementioned phase was monitored. The data, digitised at a sampling rate of 6 kS/s, was then analysed with the procedure described in the previous section in order both to detect and measure the expected inter-harmonics superimposed on the signal. Owing to its duration (about 5 minutes), it was not possible to analyse the entire transient current simultaneously; it was necessary to split it into contiguous records.

For the sake of brevity, only the results related to that slice of the transient current evolving within the time interval ranging from 100 s up to 105 s are given (Figs. 8, 9 and 10). In particular, Fig. 8 gives the evolution versus time of the aforementioned slice. Fig. 9 presents the results obtained from the application of the STFT to the same slice; the length of the window adopted for the implementation of the STFT is equal to a quarter of the entire slice. Besides the fundamental at 300 Hz, Fig. 9 shows a significant inter-harmonic the frequency of which changes in time and is located within 40÷50 Hz. At last, the results furnished by the proposed measurement procedure, and zoomed in frequency are depicted in Fig. 10. It is evident how the evolution versus time of the aforementioned inter-harmonic is better resolved than that provided by the STFT.

The analysis of the entire transient current put into evidence the presence of several inter-harmonics characterised by multifaceted evolutions: some of them showed a frequency increase versus time, others of them a decrease; some appeared at very low frequency, others came within reach of the fundamental.

In conclusion, according to the obtained results, it is worth highlighting that inter-harmonics' evolution versus time is so complex that measurement procedures like the proposed one are welcome for plant managers!

### 5 CONCLUSIONS

Standards and Recommendations are not prepared to suggest procedures and instruments able to evaluate the level of inter-harmonics, more than ever if non-stationary inter-harmonics are involved. For this reason, a new procedure for inter-harmonic detection and estimation has been presented.

Simulations and on-field measurements evidenced that the procedure properly works for measuring both stationary and non-stationary inter-harmonics. Specifically, it succeeded in revealing and measuring undesired inter-harmonics produced by an actual power plant, which cause troubles on the mains with the introduction of electromagnetic interference.

The obtained results are hopeful. In particular, a satisfactory accuracy was proved in the measurement of non-stationary inter-harmonics characterised either by amplitude or frequency variation versus time.

The research is still in advance paying attention both to (i) exhaustively assess the performance of the proposed procedure, and (ii) increase its measurement accuracy in the presence of inter-harmonics the amplitude and frequency of which simultaneously vary versus time.

### APPENDIX

Time-Frequency Representations (TFRs) are two dimensional functions of time  $t$  and frequency  $f$  that indicate how the frequency content of a signal  $s(t)$  changes over time. The simplest TFR is the *spectrogram*,  $S_s(t, f)$ , the squared magnitude of the STFT

$$S_s(t, f) = \int s(\mathbf{t})w^*(\mathbf{t} - t)e^{-j2\pi f t} dt$$

The classical time-frequency resolution trade-off of the *spectrogram*, which is controlled by the analysis window,  $w$ , has prompted the development of more advanced bilinear TFRs, including the

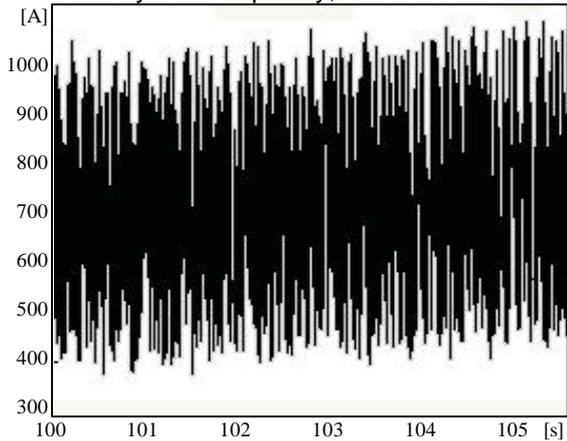


Figure 8. A slice of the analysed current.

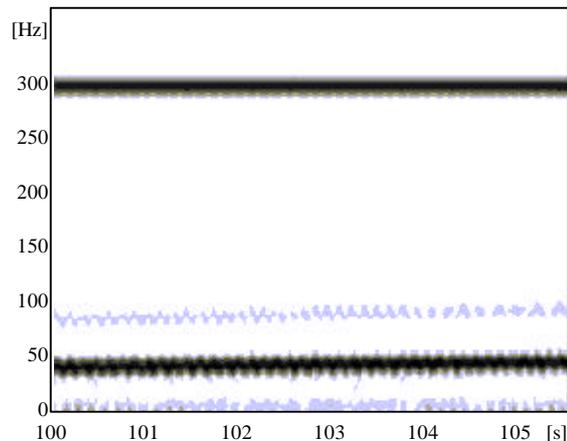


Figure 9. STFT results of the analysed current.

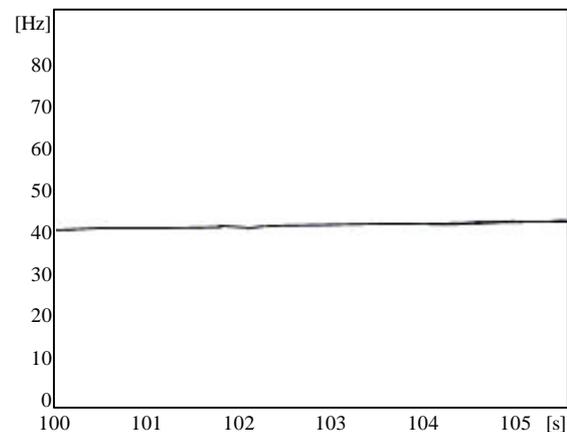


Figure 10. Results of the proposed procedure.

*Wigner-Ville distribution*

$$W_s(t, f) = \int s\left(t + \frac{t}{2}\right) s^*\left(t - \frac{t}{2}\right) e^{-j2\pi f t} dt \quad (2)$$

This TFR can be interpreted as a STFT with the window matched to the signal. While the *Wigner-Ville distribution* is highly concentrated, it generates cross-components due to its nonlinearity and is very sensitive to noise [9].

Both *spectrogram* and *Wigner-Ville distribution* belong to *Cohen's class* of TFRs. The *Wigner-Ville distribution* can be interpreted as the central, generating member of this class, with each *Cohen's class* TFR,  $C$ , obtained via two-dimensional correlation

$$C_s(t, f) = \iint W_s(\mathbf{t}, \mathbf{u}) \mathbf{f}(\mathbf{t} - \mathbf{t}, \mathbf{u} - f) dt du \quad (3)$$

with  $F$  the kernel of  $C$ .

*Cohen's class* TFRs have a simple interpretation as a *smoothed Wigner-Ville distribution*. To compute a TFR at the point  $(t, f)$  in the time-frequency using (3), the kernel  $F$  is translated to  $(t, f)$ , and multiplied with the *Wigner-Ville distribution*,  $W_s$ ; the product is then integrated and the result is placed at the point  $(t, f)$ . For low-pass kernels  $F$ , smoothing suppresses cross-components and reduces noise sensitivity in the *Wigner-Ville distribution*, but simultaneously "smears" the time-frequency representation [9].

The idea behind reassignment is simple and ingenious. The value of the *center of mass* of the product between  $W_s$  and  $F$  is associated to the center point  $(t, f)$  in the place of the integral of the same product. Reassignment smoothes the *Wigner-Ville distribution*, but then refocuses the TFR back to the true regions of support of the signal components. For many "real world" signals, a strongly concentrated TFR will result. It is worth noting that a reassigned distribution is highly linear, and no longer merely quadratic [10].

**REFERENCES**

- [1] *Electromagnetic compatibility (EMC) - Part 2: Environment - Section 2: Compatibility levels for low-frequency conducted disturbances and signalling in public low-voltage power supply systems*, IEC Standard 1000-2-2, 1990.
- [2] P. Daponte, G. Falcomatà, A. Testa, "A multiple deep attenuation frequency window for harmonic analysis in power systems", *IEEE Trans. on Power Delivery*, vol.9, No.2, April 1994, pp.863-871.
- [3] T. Lobos, T. Kozina, H.J. Koglin, "Power system harmonics estimation using linear least squares method and SVD", *Proc. of IEEE IMTC/99*, Venice, Italy, May 24-26 1999, vol.2, pp.789-794.
- [4] R. Carbone, et al., "Iterative harmonics and interharmonics analysis in multiconverter industrial systems", *Proc. of 8<sup>th</sup> Int. Conf. On Harmonics and Quality of Power*, Athens, Greece 1998, vol.1, pp.432-438.
- [5] L. Angrisani, P. Daponte, M. D'Apuzzo, A. Testa, "A measurement method based on the wavelet transform for power quality analysis," *IEEE Trans. on Power Delivery*, vol.13, No.4, October 1998, pp.990-998.
- [6] *Electromagnetic compatibility (EMC) - Part 4: Testing and measurement techniques - Section 7: General guide on harmonics and interharmonics measurements and instrumentation, for power supply systems and equipment connected*, IEC Standard 1000-4-7, 1991.
- [7] X. Dai, R. Gretschi, "Quasi-synchronous sampling algorithm and its applications", *IEEE Trans on Instr. and Meas.*, vol.43, No.2, April 1994, pp.204-209.
- [8] R. Carbone, et al., "Interharmonic distortion in the static starting-up system of a hydro-electric pumped-storage power station" *Proc. of IEEE ICHQP*, Las Vegas, Nevada, USA, October 16-18, 1996;
- [9] F. Hlawatsch, G.F. Boudreaux-Bartels, "Linear and quadratic time-frequency signal representations", *IEEE Signal Processing Magazine*, vol.9, No.2, April 1992, pp.21-67.
- [10] F. Auger, P. Flandrin, "Improving the readability of time-frequency and time-scale representations by the reassignment method", *IEEE Trans. ASSP*, vol.43, No.5, May 1995, pp.1068-1089.

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