20th IMEKO TC4 International Symposium and
18th International Workshop on ADC Modelling and Testing
Research on Electric and Electronic Measurement for the Economic Upturn
Benevento, Italy, September 15-17, 2014

A Compressed Sampling-Based Method Compliant with IEC 61000-4-30 for Harmonic and Interharmonic Measurements

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***Abstract* – The paper deals with the problem of measuring harmonic and interharmonic pollution in electrical power delivery systems. The attention is specifically focused on the possibility of exploiting the compressed sampling in order to implement cost-effective nodes for distributed acquisition of the voltage signals. Differently from the traditional distributed measurement systems, the proposed approach should allow a dramatic cost reduction of the monitoring network. According to the compressed sampling protocol, the operations of distributed nodes will, in fact, be limited to random digitization and transmission of few samples for each voltage line; no high performance architectures should, thus, be necessary, with a consequent money saving. Assessing the compliance of the achieved measurements with the current standards turns out to be mandatory, thus verifying the absence of artifacts introduced by the adopted compressed sampling approach.**

Results obtained in numerical and experimental tests have highlight the promising performance of the proposed approach, thus suggesting its implementation in an actual measurement instrument.

I. INTRODUCTION

In recent years significant change in the power grid for the distribution of electrical energy have been observed. Thanks to liberalization of the electrical market and the incentives offered to the production of energy from renewable sources, the number of medium and small producers has increased. Moreover, with the development of communication technology, the transmission grid has been increasingly equipped with automated devices capable of monitoring and transmitting some information about the grid and, in some cases, to control the actuation devices connected to the grid itself. In this scenario, the term smart grid was born, used to describe a power grid that can cleverly manage itself, performing the appropriate actions as a result of events occurring on the grid [1]. With the evolution of the smart grid, power quality issues became even more important; assessing the quality of electrical power delivered to customers connected to the grid should be advisable to prevent harmful fault on their equipment. As an example, Recently, the increasing use of electronic devices powered by Switched-Mode Power Supply (SMPS), the whole replacement of old tungsten filament bulbs with modern Compact Fluorescent Lamp (CFL), and the large use of DC/AC inverter for connecting solar panels to transmission grid, are giving some concerns on the generation of PQ disturbances. In particular, it is worth noting, that these equipments can generate harmonic and interharmonic disturbances [2]-[3]. As a consequence, the problem of the presence of harmonic and interharmonic disturbances is becoming very relevant, making to grow the attention towards their measurement and the identification of the causes of generation [4].

As it can be expected, the widest the grid, the largest the number of nodes required for its monitoring. According to the current approach for distributed monitoring, the nodes will locally measure the quantities of interest and send them back to central collecting unit. Even though the cost of the single nodes should not be excessive (moving from 10 k€ for high performance meter down to few hundreds of euro for devices not compliant with the current measurement standards), deploying thousands of such devices turns rapidly to be too expensive.

To overcome the considered limitation, the authors suggest the possibility to move towards a different approach for monitoring grid deployed on wide geographical areas. In particular, the adoption of low-cost, low-performance systems (mandated only to acquire the voltage signals of interest) is proposed. To limit the burden associated with the transmission of the acquired samples to a central processing unit, compressed sampling techniques are suggested to make it possible of recovering the whole signal of interest from a limited number of samples actually acquired on the network. This way, assessing the compliance with the standards IEC 61000-4-30 (defining methods and uncertainty for power quality) and EN 50160 (defining the maximum limits that

ISBN-14: 978-92-990073-2-7

grid features have not to overcome) of the measurements carried out on the recovered signal turns out to be mandatory [5]-[9].

In their previous experience [10]-[12], the authors verified the capability of CS-based acquisition approach of correctly measuring the root-mean-square amplitude of voltage waveforms. In the following, the attention is focused of harmonic and interharmonic voltage pollution; in particular, the authors assessed in a number of tests that the CS-based approach does not introduce measurement artifacts capable of shifting the measured amplitude of the spectral component of interest of a quantity greater than the assigned uncertainty.

II. MEASUREMENT METHODS AND ASSESSMENT CRITERIA FOR POWER QUALITY APPLICATIONS

Measurement methods for power quality applications are defined in the IEC 61000-4-30 standard, *"Testing and measurement techniques-Power quality measurement methods"*. In particular, this standard defines the methods for measurement and interpretation of results for power quality parameters in 50/60 Hz a.c. power supply systems. Measurement methods and desired uncertainties are described for each relevant parameter to assure reliable and repeatable results, regardless its implementation. With specific regard to measurements of the spectral content of the voltage signal, the IEC 61000-4-30 refers to IEC 61000-4-7 for measurement setup, assessment of harmonic emissions and accuracy requirements. As for the accuracy, its value is given in Tab.I for different conditions of meter class and component amplitude (U_m) with respect to the rated rms voltage (U_{nom}). Moreover, the IEC 61000-4-7 standard prescribes a DFT-based method (usually referred to as grouping and subgrouping) for amplitude measurement of spectral components even in the presence of slight fluctuation of their frequency. In particular, with regard to the harmonic components, amplitude of the h^{th} component $X_{hsg,h}$ is achieved by means of the following subgroup expression

$$X_{hsg,h}^2 = \sum_{i=-1}^{1} X_{k_h+i}^2 \qquad (1)$$

where k_h stands for the DFT bin k corresponding to h^{th} harmonic. In a similar way, the h^{th} interharmonic subgroup is defined according to

$$X_{isg,h}^2 = \sum_{i=2}^{8} X_{k_h+i}^2 \qquad (2)$$

Tab.I Limits of desired uncertainty related to class A and B meters according to the standard IE 61000-4-7.

Class	*Measurement*	*Conditions*	*Maximum error*
A	*Voltage*	$U_m \geq 1\%\ U_{nom}$	$\pm 5\ \%\ U_m$
		$U_m < 1\%\ U_{nom}$	$\pm 0.05\ \%\ U_{nom}$
B	*Voltage*	$U_m \geq 3\%\ U_{nom}$	$\pm 5\ \%\ U_m$
		$U_m < 3\%\ U_{nom}$	$\pm 0.15\ \%\ U_{nom}$

where the bin limits of the sum are set according to the prescribed frequency resolution of 5 Hz.

While IEC 61000-4-30 defines the measurement methods, the EN 50160 standard defines, in European countries, the main voltage characteristics of electricity supplied by public distribution network, at user's supply terminals in low, medium and high voltage, under normal operating conditions. In particular, this standard defines the limits or values concerning frequency, magnitude, waveform, symmetry of the line voltages, within the voltage characteristic should remain. As shown in the successive experimental tests, those values can be adopted to define tests signal to be adopted for the performance assessment of the measurement method.

With specific regard to spectral harmonic content, under normal operating condition, during each period of a week, the 95% of RMS values of each individual harmonic voltage, aggregated over time intervals of 10 minutes, shall be less than or equal to the values given in Tab.II. Moreover, the total harmonic distortion of the supply voltage (including harmonics up to the order 40) shall be less than or equal to 8%. The standard not furnish values for harmonics of order higher than 25, as they are usually small, but largely unpredictable due to resonance effects.

III. PROPOSED METHOD

Traditional measurement instruments, that are compliant with IEC 61000-4-30 standard, after a suitable synchronization pre-processing, perform acquisition at a sample rate according to sampling approach based on the *Nyquist–Shannon* theorem. Thus, in order to measure harmonics order up to 50, a suitable A/D converter has to be adopted.

For each acquisition of 10/12 time periods of the input signal, the measurement instruments determine the amplitude of spectral components by means a DFT-based algorithm, according to equations (1) and (2). For long time analysis, this approach requires large memory depth, that notably increases the cost of each instrument. To overcome this limitations the data are aggregated in time

Tab.II – Limit values of individual harmonic voltages at supply terminals for order up to 25 given in percent of the fundamental amplitude u_1

Odd harmonics				Even harmonics	
Not multiples of 3		Multiples of 3			
Order *h*	Relative amplitude u_h	Order h	Relative amplitude u_h	Order h	Relative amplitude u_h
5	6.0 %	3	5.0 %	2	2.0 %
7	5.0 %	9	1.5 %	4	1.0 %
11	3.5 %	15	0.5 %	6 ... 24	0.5 %
13	3.0 %	21	0.5 %		
17	2.0 %				
19	1.5 %				
23	1.5 %				
25	1.5 %				

intervals of 10 minutes. As a consequence, the details of the wave shape are not stored and are permanently lost once data have been aggregated. In this paper, the authors exploit the possible application of the CS, an innovative paradigm of acquisition, in order to implement a cost-effective Data Acquisition System (DAS) that does not need of high performance architecture for the acquisition of the voltage signals. CS approach is a technique that allows to recover a given *N*-dimensional signal through a number of sample $\boldsymbol{M}$, which is much smaller than $\boldsymbol{N}$ if a discrete signal $\boldsymbol{x} \in \boldsymbol{R}^{\boldsymbol{N}}$ can be expressed as:

$$\mathbf{x} = \boldsymbol{\Psi}\mathbf{s} \tag{3}$$

where $\boldsymbol{\Psi} \in \boldsymbol{R}^{NxN}$ is a transformation matrix and the vector $\boldsymbol{s} \in \boldsymbol{R}^{\boldsymbol{N}}$ is ***k-sparse***, which mean it exhibits $\boldsymbol{k}$ significant components [13]. As an example, a sinusoidal signal is characterized by an endless evolution versus time, while its Fourier transform contains the same information in only two coefficients different from zero. According to CS theory, the vector $\boldsymbol{s} \in \boldsymbol{R}^{\boldsymbol{N}}$ can be obtained from a number $\boldsymbol{M}$ of random projection of signal $\boldsymbol{x} \in \boldsymbol{R}^{\boldsymbol{N}}$. From a mathematical point of view, time–domain sampling $\boldsymbol{M}$ samples (with $\boldsymbol{M} \ll \boldsymbol{N}$) reduced of the signal of interest $\boldsymbol{x} \in \boldsymbol{R}^{\boldsymbol{N}}$ sufficient to correct reconstruct it, can be expressed as:

$$\boldsymbol{y} = \boldsymbol{\Phi}\boldsymbol{x} \tag{4}$$

where $\boldsymbol{y} \in \boldsymbol{R}^{\boldsymbol{M}}$ is the vector of measurements, $\boldsymbol{\Phi} \in \boldsymbol{R}^{MxN}$, is the sampling matrix, that perform a random sampling of the input signal $\boldsymbol{x}$ [14]. Now, by combing eq.(2) and eq.(3) the following expression is obtained:

$$\boldsymbol{y} = \boldsymbol{\Phi}\boldsymbol{x} = \boldsymbol{\Phi}\boldsymbol{\Psi}\boldsymbol{s} \tag{5}$$

Let us introduce the sensing matrix $\boldsymbol{A} \in \boldsymbol{R}^{MxN}$ given from the matrix product ΦΨ, obtaing:

$$\boldsymbol{y} = \mathbf{A}\mathbf{s} \tag{6}$$

This system is ill-posed since the number of equations $\boldsymbol{M}$ is smaller than the number of unknowns $\boldsymbol{N}$. However, if $\boldsymbol{s}$ is sparse, it has been demonstrated that eq. (6) can be solved by means CS-Solvers[15].

With refer to the specific problem, input signals in time-domain are made by sums of sinusoidal wave shapes at harmonic and interharmonic frequencies. Thus, by choosing $\boldsymbol{\Psi}$ as DFT, matrix $\mathbf{A}$ becomes a random sub-matrix of the DFT, and vector sparse $\boldsymbol{s}$ is the magnitude spectrum of $\boldsymbol{x}$. In Fig.1 the proposed architecture is shown. Two main blocks can be distinguished:(i) the DAS system, that perform sampling by means CS approach; (ii) the Personal computer (PC) that receives the compressed vector $\boldsymbol{y}$ of the measurements and recovers the magnitude spectrum of $\boldsymbol{x}$, solving eq.(6) by means the CS-Solver. The input signal is processed to determine the carrier frequency. Thus, the Sampling Frequency Generation Block can generate a suitable sampling frequency to acquire an integer number of

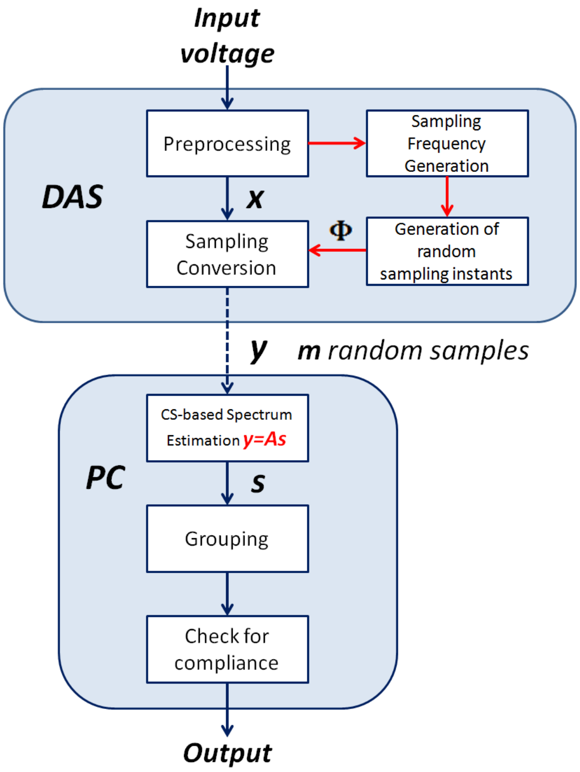

Fig.1 Proposed architecture based on CS approach.

periods of the input signal. Different from traditional measurement instruments, sampling frequency is used as resolution time bases $\boldsymbol{T_C}$ for generating of the random sampling instants. The $\boldsymbol{M}$ sampling instants $\boldsymbol{t_i}$ are randomly chosen throughout the considered observation interval $\boldsymbol{T_w}$ equal to $\boldsymbol{N}$ times $\boldsymbol{T_c}$. The random sampling instants are integer multiple of the resolution time bases $\boldsymbol{T_C}$:

$$t_i = k_i T_c, \quad k_i \in [0, n-1] \text{ and } \mathrm{i} = 1, .., m \tag{7}$$

In this way the DAS has to collect only $\boldsymbol{M}$ samples instead $\boldsymbol{N}$ (with $\boldsymbol{M} \ll \boldsymbol{N}$).

Once the random sampling is performed, the DAS transmits the vector of measurement $\boldsymbol{y}$ to the data concentrator, that could be a Personal Computer (PC) with high processing capability, for the successive recovery of the magnitude spectrum $\boldsymbol{s}$ of the input voltage. The amplitude of harmonic and interharmonic subgroups is achieved by means eq.(1) and eq.(2). Thanks to the proposed method it is possible to realize low-cost DAS systems suitable for distributed signal acquisition in smart grid environment.

IV. RESULTS

To assess the performance of the proposed method, a number of tests, conducted either in numerical or actual experiments, have been carried out; some relevant results are given in the following. To verify the absence of artifacts introduced by the CS, different measurement conditions, in terms of:

(i) Harmonic content (amplitude, phase angle, harmonic order);
(ii) Interharmonic content (amplitude, frequency);
(iii) Vertical resolution of A/D converter [bit];
(iv) Acquired random samples m

have been taken into account.

As performance factor, the difference between measured and nominal amplitude of each harmonic and/or interharmonic (referred to as measured error) have been calculated and compared with the maximum error defined in the IEC 61000-4-7 for class A meters. As regard the observation interval and sample rate, they have been set equal to 200 ms and 10.24 kSa/s; it has been so possible to recover the spectrum of the nominal signal on 2048 bins with a frequency resolution of 5 Hz, compliant with what is stated in IEC 61000-4-7. Considered values has been chosen to operate in conditions as close as possible to those adopted by some of the most performing instrumentation for power quality measurements [16],[17].

A. Numerical tests

As an example, Tab.III reports the results obtained for different values of acquired samples (100 and 200 respectively) in numerical tests conducted on a nominal signal, whose spectral component amplitudes match the values indicated as limit in IEC 50160; vertical resolution has been set to 12 bits. Fig.2 shows the corresponding nominal signal along with the 200 acquired random samples. As it can be appreciated, most of the amplitude measures are not compliant with IEC 61000-4-7 if the spectrum is recovered starting from 100 random samples. On the contrary, increasing the number of acquired samples to 200 (with a compression ratio of about 90%) allowed to accurately estimate the RMS amplitude of harmonic components; measured error always lower than the maximum one have, in fact, been experienced whatever the harmonic order.

B. Experimental tests

As stated above, a number of tests have also been conducted on actual power supply signals; during this preliminary stages, voltage signals have been acquired by means of a data acquisition system NI9215 by National Instruments with a uniform sample rate of 10 kSa/s and a vertical resolution of 16 bit. To assure a frequency resolution compliant to what suggested by IEC 61000-4-7, 2000 samples has been acquired during the observation interval of 200 ms; CS-acquisition has then been simulated by randomly extracting up to 500 samples from the acquired record. The results provided by the proposed method have been compared to those granted by the application of traditional discrete Fourier transform on the whole acquired record.

As an example, Tab.IV reports the comparison results in the presence of 250 random acquired samples; as it can be appreciated differences between DFT-based and CS-based measurements always lower than the maximum error prescribed by the standard have been encountered, thus confirming the promising performance of the proposed method.

Tab. III - Results obtained for different values of acquired samples (100 and 200 respectively) in numerical tests conducted on a nominal signal

Order of Harm	***100 acquired random samples***				***200 acquired random samples***			
	Measured Amplitude [V]	*Maximum Error [V]*	*Measured Error [V]*	*Compliance Class A*	*Measured Amplitude [V]*	*Maximum Error [V]*	*Measured Error [V]*	*Compliance Class A*
2	2,40	0,23	2,20	**N**	4,58	0,23	0,02	**Y**
3	9,52	0,57	1,98	**N**	11,48	0,57	0,02	**Y**
4	0,00	0,12	2,30	**N**	2,29	0,12	0,01	**Y**
5	11,70	0,69	2,10	**N**	13,80	0,69	0,00	**Y**
6	0,00	0,12	1,15	**N**	1,19	0,12	0,04	**Y**
7	9,80	0,57	1,70	**N**	11,50	0,57	0,00	**Y**
8	0,33	0,12	0,82	**N**	1,17	0,12	0,02	**Y**
9	3,61	0,17	0,16	**Y**	3,50	0,17	0,05	**Y**
10	0,46	0,12	0,69	**N**	1,19	0,12	0,04	**Y**
11	6,48	0,40	1,57	**N**	8,09	0,40	0,04	**Y**
12	0,39	0,12	0,76	**N**	1,19	0,12	0,04	**Y**
13	6,27	0,34	0,63	**N**	6,89	0,34	0,01	**Y**
14	0,00	0,12	1,15	**N**	1,19	0,12	0,04	**Y**
15	0,70	0,12	0,45	**N**	1,20	0,12	0,05	**Y**
16	0,00	0,12	1,15	**N**	1,20	0,12	0,05	**Y**
17	4,89	0,23	0,29	**N**	4,59	0,23	0,01	**Y**
18	0,40	1,12	0,75	**Y**	1,20	1,12	0,05	**Y**
19	2,01	0,17	1,44	**N**	3,50	0,17	0,05	**Y**
20	1,12	0,12	0,03	**Y**	1,20	0,12	0,05	**Y**
21	1,33	0,12	0,18	**N**	1,20	0,12	0,05	**Y**
22	1,06	0,12	0,09	**Y**	1,19	0,12	0,04	**Y**
23	2,35	0,17	1,10	**N**	3,49	0,17	0,04	**Y**
24	0,00	0,12	1,15	**N**	1,20	0,12	0,05	**Y**
25	0,76	0,17	2,69	**N**	3,49	0,17	0,04	**Y**

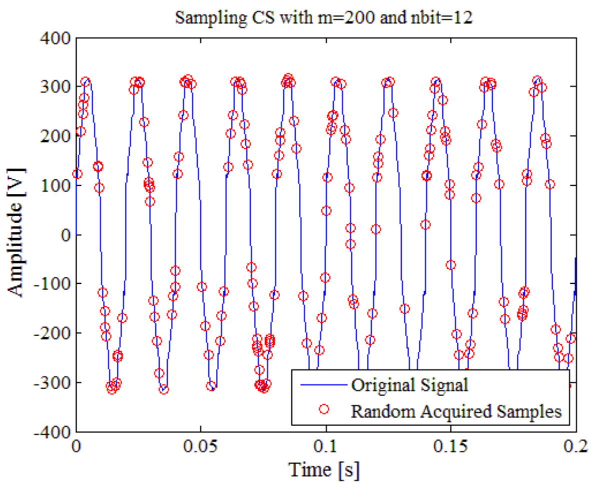

Fig.2 Original signal (blue line) along with the random samples (red circles) acquired according to the CS approach.

Tab IV - Comparison results in the presence of 250 random acquired samples

Order of Harm	*Measured Amplitude DFT [V]*	*Measured Amplitude CS-bases [V]*	*Maximum Difference [V]*	*Measured Difference [V]*	**Compliance Class A**
2	0,09	0,01	0,12	0,08	**Y**
3	1,60	1,53	0,12	0,07	**Y**
4	0,15	0,14	0,12	0,01	**Y**
5	4,28	4,21	0,21	0,07	**Y**
6	0,04	0,00	0,12	0,04	**Y**
7	0,97	0,89	0,12	0,08	**Y**
8	0,06	0,00	0,12	0,06	**Y**
9	0,76	0,72	0,12	0,04	**Y**
10	0,03	0,00	0,12	0,03	**Y**
11	0,64	0,61	0,12	0,03	**Y**
12	0,02	0,00	0,12	0,02	**Y**
13	0,16	0,15	0,12	0,01	**Y**
14	0,03	0,01	0,12	0,02	**Y**
15	0,12	0,06	0,12	0,06	**Y**
16	0,00	0,02	0,12	0,02	**Y**
17	0,16	0,12	0,12	0,04	**Y**
18	0,01	0,00	0,12	0,01	**Y**
19	0,11	0,06	0,12	0,05	**Y**
20	0,01	0,00	0,12	0,01	**Y**
21	0,04	0,00	0,12	0,04	**Y**
22	0,01	0,00	0,12	0,01	**Y**
23	0,09	0,01	0,12	0,08	**Y**
24	0,01	0,00	0,12	0,01	**Y**
25	0,01	0,00	0,12	0,01	**Y**

V. CONCLUSIONS

The paper present an application of the compressed sampling techniques to power quality; the attention is specifically focused on the measurement of harmonic and interharmonic components compliant with the current standard IEC 61000-4-30. Preliminary tests showed the efficacy of the proposed method, thus making it possible of realizing low-cost DAS systems for distributed signal acquisition in smart grid environment.

Ongoing activity are mainly concerned with (i) the optimization of the random sampling stage, in order to minimize the number of random samples need to perform measurements compliant with the considered standards, and (ii) the realization of a low-cost CS-based compliant DAS prototype.

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