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# A STUDY ON THE FEASIBILITY AND EFFECTIVENESS OF DIGITAL FILTER APPLICATION FOR HARMONIC AND INTERHARMONIC MEASUREMENT IN COMPLIANCE WITH IEC 61000-4-7

Large scale monitoring of power quality in electrical power plants is nowadays a pressing need due to the liberalization of the electrical market in many countries and the deeper interconnections of electrical networks. Many instruments are today available on the market. Even if they provide good accuracy and measurement capability, they are generally developed for single point measurements. Their use in large scale monitoring leads to high costs. In this framework research activity, the authors aim at the realization of a measurement instrument for power quality monitoring in compliance with IEC 61000-4-30 and 61000-4-7 standards capable of granting good accuracy, satisfying repeatability, and cost effectiveness since the use in large scale monitoring is allowed. In this paper the attention is paid to the measurement algorithm to be adopted. The use of an alternative measurement approach with respect to the FFT one is proposed. Digital filters shaped on the harmonic group are thoroughly optimized for grouping measurements required by the IEC EN 61000-4-7 standard both in simulation and emulation environments. The obtained results confirm the advantages of the proposal.

Keywords: digital filters, power quality, waveform distortion analysis, power system measurement

## 1. INTRODUCTION

The quality of voltage waveforms is nowadays an important issue for power system utilities, electric energy users and also for the manufacturers of electric and electronic equipment. The main reasons are the increasing number of power quality (PQ) problems linked to the modern power electronic devices, the susceptibility of loads and the incoming new liberalized competitive markets, where electric disturbances have significant economic consequences.

In the past, PQ was often seen as an implicit duty of system operators; today, with the liberalization of the energy markets in many countries, quality objectives have become more and more explicit either in the form of contracts negotiated with customers, or as definite objectives agreed with the regulator. A number of regulators have already defined, or have planned to establish PQ objectives (e.g. supply continuity and voltage quality) to be met by the electricity supply systems. In some countries, regulators may even impose penalties in the case of non-observance of the PQ objectives.

It is indispensable for meeting PQ targets that the interested parties agree on the method of gathering and presenting estimated data. For these reasons standards [1–4] regulate PQ disturbances by means of suitable indices. Monitoring the electric system according to these standards gives the chance of improving the relationship among all the actors on electric markets.

The liberalization of the energy market has emphasized another aspect of PQ problems: the correct measure of electric energy under non-sinusoidal condition. This problem is highlighted by different published papers, a good summary is provided in [5]. An initial possible approach for the standardization of the metric to be used for estimating the electric power under non-sinusoidal condition is provided in [6]. In this context, in order to make the energy measurement correct and traceable, the effects of PQ disturbances on both active and reactive electric energies have to be assessed as well as possible.

In this scenario, the availability of a measurement instrument able to satisfy the standard requirements on the measure of PQ disturbances and characterized by a cost that allows both a deep and distributed PQ monitor, represents an important feature.

The standards [3] and [4] define both the methods and the performance specification for measurement and interpretation of results for power quality parameters. As is well known, there are two main categories of PQ disturbances: variations and events, belonging to steady state and transient phenomena respectively. Variations can be divided in two categories defined as harmonic and interharmonic distortions, while events comprise interruptions, dips, sags, swells, and so on.

As regards harmonic and interharmonic distortion, requirements for both measurement instruments and methods are defined in [4]. This standard suggests the realization of a measurement instrument based on a Fast Fourier Transform (FFT) approach, but it does not preclude the application of other analysis principles. In this last case the standard imposes that the instrument specifications shall state the uncertainty caused by all influencing factors including the non-stationary characteristic of the signal, the aliasing phenomenon, and the loss of synchronization.

The crucial drawback of the FFT method is that the length of the window is related to the frequency resolution. Moreover, to ensure the accuracy of FFT, the sampling interval of analysis should be an exact integer multiple of the waveform fundamental period. For these reasons, a crucial point in the realization of an accurate PQ analyzer is the synchronization process. This is not an easy task in the presence of harmonic and interharmonic distortion so that with respect to the suggestion given in [4], additional hardware/software solutions have to be enforced [7, 8].

Taking into account the above-mentioned consideration, the processing and memory capabilities related to synchronization and FFT analysis required by the compliance with [3] and [4], deliver some issues that may limit the cost-effectiveness of the measurement solutions present on the market. In fact, in a three-phase system with neutral wire, four currents and four voltages have to be detected, synchronized, measured and analyzed with good accuracy and spectral resolution. This means that the processing system, usually a microcontroller, has to be able to: (i) estimate the frequency of incoming signals and change (in a digital or analog way) the sampling frequency; (ii) store and manage a large number of data; (iii) detect and classify events and (iv) process many complex computations in a very short time.

Several approaches, based on alternative analysis principles, for automatic detection and classification of PQ disturbances were proposed in literature [9–20].

Some of them are based on time-frequency representations such as wavelet transform or short time Fourier transform, which are assisted e.g. by neural networks or fuzzy expert systems. Methods based on pattern recognition using support vector machines are also used as useful techniques for disturbance classifications. Other approaches apply mathematical morphology and/or the calculation of the RMS (Root Mean Square) value.

Other useful solutions proposed for PQ monitoring are based on the use of digital filters [16–20]: different approaches are used depending on the type and shape of the digital filter as well as the power quality disturbances that are to be estimated.

Although the number of methods presented in the literature, the detection and classification problem in PQ is still an open question and a useful monitoring system is still missing. This is particularly true if requirements like compliance with [4] and low cost are considered.

With the aim of realizing a low-cost class I PQ instrument, the authors, starting from their past experience in this field [21–26], propose a study of the feasibility of an original digital filter approach to monitor harmonic and interharmonic distortions, according to IEC standard [4].

A number of digital filters, characterized by different types, shapes and orders, were considered and optimized. The effectiveness of the chosen solution was confirmed by the analysis of the digital filter response and its comparison with the FFT approach. Tests were made on both simulated and emulated signals characterized by typical harmonic and interharmonic contents.

## 2. THEORETICAL BACKGROUND

Waveform distortion disturbance in a power line is defined as the deviation of the signal from a sinusoid. As is well known, the standard IEC 61000-4-7 [4] defines the requirements for both harmonic and interharmonic measurement and instrumentation. It specifies the following concepts and requirements:

(i) The general structure of the measurement instrumentation; it comprises: input circuits with anti-aliasing filter, an analog to digital converter including a sample and hold unit, synchronization and window-shaping unit (if necessary), a processing unit. It considers an FFT approach to estimate spectral lines: this choice imposes the need of accurate synchronization to avoid spectral leakage troubles.

(ii) The accuracy of instrumentation; two classes of accuracy are suggested for instrumentation measuring harmonic distortion. Table 1 shows the maximum allowable errors for voltage, current and power measurements in different working conditions. Class II instruments are recommended for general surveys while for the cases where precise measurements are necessary, such as for verifying compliance with standards, resolving disputes, etc, Class I instruments are recommended.

(iii) The characteristics of the signals to be measured; this standard distinguishes between signals (harmonics and interharmonics) below the harmonic frequency range (approximately 2 kHz) and other components above the harmonic frequency range but below the upper limit of the low-frequency range (approximately 9 kHz). The other components are spectral line of the signals with frequencies exceeding the harmonic frequency range (approximately 2 kHz) but below the upper limit of the low-frequency range (approximately 9 kHz).

(iv) The types of measurement; requirements for the measurements of the signals defined at point (iii) are given. Particular attention is devoted to harmonic and interharmonic measurements while just some consideration is given for the other components.

Table 1. Accuracy requirements for harmonic measurement instruments according to IEC 61000-4-7 standard.

| Class | Measurement | Voltage | | Current | | Power | |
|---|---|---|---|---|---|---|---|
| I | Condition | $U_m \geq 1\%\ U_{nom}$ | $U_m < 1\%\ U_{nom}$ | $I_m \geq 3\%\ I_{nom}$ | $I_m < 3\%\ I_{nom}$ | $P_m \geq 150$ W | $P_m < 150$ W |
| | Maximum Error | $\pm 5\%\ U_m$ | $\pm 0.05\ U_{nom}$ | $\pm 5\%\ I_m$ | $\pm 0.15\%\ I_{nom}$ | $\pm 1\%\ P_{nom}$ | $\pm 1.5$ W |
| II | Condition | $U_m \geq 3\%\ U_{nom}$ | $U_m < 3\%\ U_{nom}$ | $I_m \geq 10\%\ I_{nom}$ | $I_m < 10\%\ I_{nom}$ | – | – |
| | Maximum Error | $\pm 5\%\ U_m$ | $\pm 0.15\ U_{nom}$ | $\pm 5\%\ I_m$ | $\pm 0.5\%\ I_{nom}$ | – | – |
| $U_m$, $I_m$, $P_m$ measured values; $U_{nom}$, $I_{nom}$, $P_{nom}$ nominal values of the measurement instrument | | | | | | | |

For practical purpose, this standard defines the harmonic (interharmonic) frequency as an integer (not integer) multiple of the fundamental frequency. With reference to a FFT using a time window of 200 ms equivalent to ten (50 Hz) or twelve (60 Hz) fundamental periods, each spectral component shall be measured with a frequency resolution of 5 Hz. Spectral lines have to be suitably processed in order to obtain desired harmonic and interharmonic groups/subgroups (e.g. see Fig. 1). This task provides an overall value which includes the effects of fluctuations of the harmonic components.

The amplitudes of the $n^{\text{th}}$ IEC harmonic $G_{sg-n}$ and interharmonic $C_{isg-n}$ subgroups can be evaluated, respectively, as:

$$G_{sg,n}^2 = \sum_{k=-1}^{1} C_{10n+k}^2, \qquad C_{isg,n}^2 = \sum_{k=2}^{8} C_{10n+k}^2,$$

where $C_{10n+k}$ are the spectral components (RMS value) of the FFT output by using a window width of 10 fundamental periods, in case of a 50 Hz system to which this paper refers.

The amplitudes of the $n^{\text{th}}$ IEC harmonic $G_{g-n}$ and interharmonic $C_{ig-n}$ groups can be evaluated, respectively, as:

$$G_{g,n}^2 = \frac{C_{10n-5}^2}{2} + \sum_{k=-4}^{4} C_{10n+k}^2 + \frac{C_{10n+5}^2}{2}, \qquad C_{ig,n}^2 = \sum_{k=1}^{9} C_{10n+k}^2,$$

where $C_{10n+k}$ are the spectral components (RMS value) of the FFT output.

Using the grouping approach, different PQ indices are defined. For instance, group (THDG) and subgroup (THDS) total harmonic distortion can be evaluated, respectively, as:

$$THDG = \sqrt{\sum_{n=2}^{H} \left(\frac{G_{gn}}{G_{g1}}\right)^2}, \qquad THDS = \sqrt{\sum_{n=2}^{H} \left(\frac{G_{gsn}}{G_{gs1}}\right)^2},$$

where $H$ is a specified order of the harmonic group/subgroup components defined in each standard concerned with limits (IEC 61000-3 series).

As regards signal components with frequencies exceeding the harmonic frequency range, the bandwidth for the grouping of these emissions should be fixed at 200 Hz. The centre frequency of the first possible group is 2.1 kHz. The total uncertainty should not exceed ± 5% of the measured value.

## 3. THE PROPOSED DIGITAL FILTERS APPROACH

The standard referenced in [4] does not preclude the application of analysis principles different from FFT provided that the general accuracy requirements are complied with.

It is possible to highlight that the grouping and subgrouping process acts as a digital filter placed on signal spectral components. Starting from this consideration the adoption of a new measurement shape that uses proper digital filter banks is proposed.

Many parameters concur in the realization of optimized filters for PQ assessment. Among others, the shape, type and order of filters have to be taken into account and properly chosen.

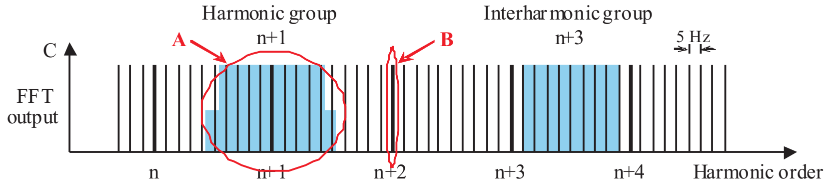


Fig. 1. Illustration of harmonic/interharmonic groups and Digital Broad (A)/Pin (B) filter shapes.

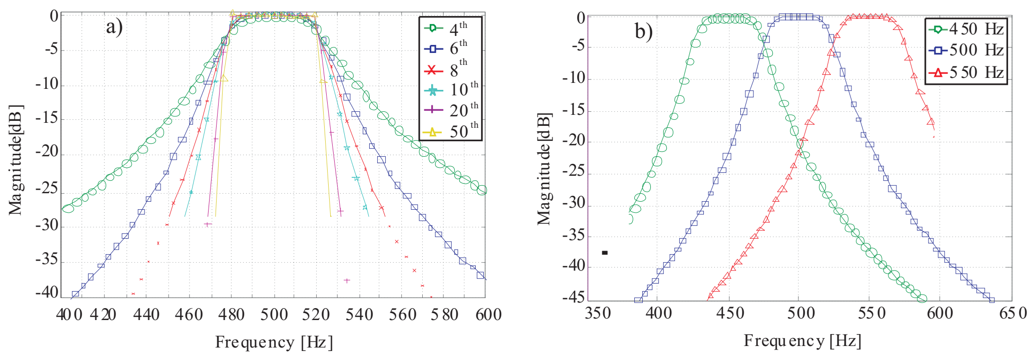


Fig. 2. (a) Magnitude response estimate of a Broad Filter centered at 500 Hz versus the selected order; (b) interference effect between adjacent filters caused by the non ideal transition band of 6th order Broad Filters.

Two shapes of digital filters could be used to achieve the frequency decomposition required by standard [4]: (i) filters tuned to a single spectral line (here in after Digital Pin Filter, DPF), and (ii) filters shaped on harmonic group (hereafter Digital Broad Filter, DBF). The former have a bandwidth of 5 Hz, equal to the required frequency resolution of each spectral line, while the bandwidth of the latter is equal to the span of harmonic or interharmonic groups/subgroups (e.g. 50 Hz for the harmonic groups). Figure 1 sketches an example for both the shape of DBF (highlighted as part A) and DPF (highlighted as part B) for harmonic and interharmonic groups. It can be highlighted that the estimate of the RMS of DBFs output gives the above defined $G_{sg,n}$, $C_{isg,n}$, $G_{g,n}$, $C_{ig,n}$ values; a suitable grouping procedure on the considered spectral lines has to be realized to obtain the desired values if a DPF is accounted for. In addition, for each harmonic and interharmonic group/subgroup, a certain number of DPFs have to be combined (e.g. eleven for the harmonic group), while only one DBF has to be set.

Two types of digital filters were considered for both DBF and DPF shapes: Finite Impulse Response (FIR) and Infinite Impulse Response (IIR) filter. To the former class belong filters as Equiripple, Interpolated FIR, etc., while in the latter are Butterworth, Chebyshev, Elliptic, Maximally Flat, etc. Fixed the shape and type of the filter, several orders were considered, looking for finding a compromise between the required metrological performance and a feasible implementation.

An in-depth analysis was carried out in order to choose and to optimally adjust all these parameters. Results reported in [27] have shown that, considering both metrological features and computational burden, the DBF shape with Butterworth implementation is more suitable than the DPF one. For these reasons the DPF shape is no longer considered in this paper.

Additional considerations are required as far as the DBF order selection is concerned. In the use of digital filtering approach for harmonics measurement according to IEC 61000-4-7 two aspects have to be considered: (i) the metrological performance in the harmonic group estimate, (ii) the capability to furnish fast responses and low settling times after events or variations.

As far as (i) is concerned, the ripple in the passband and the non ideal transition in the stopband have to be considered. Further considerations are required for the (ii) point. The IEC 61000-4-30 standard [3] imposes the harmonic estimation also in the presence of events and variation. A flag has to be set to indicate the presence of an event or a variation and the unreliability of the obtained results over a 200 ms observation period (see section 2). The presence of an event causes transients in the filter response. It is then very important that the filter is able to return in the steady state in a time as short as possible, and, in particular, shorter than 20 ms (for 50 Hz system). To the contrary, an event which occurred in a 200 ms observation period could influence the estimates of harmonic groups also for adjacent and unflagged 200 ms observation periods.

The above-mentioned considerations have driven the choice of the DBF order. Figure 2a shows an example of the magnitude response estimate of the $G_{g,10}$ harmonic group using the considered DBF centered at 500 Hz with different orders from 4 to 50; in addition, both the DBF response time and settling time, with respect to an unitary step signal, are reported in Table 2. An analysis of Fig. 2a and Table 2 highlights that an order of the DBF equal to six gives a good compromise between metrological performance and settling time. In particular, it allows: (i) sufficient metrological performance, presenting very low ripple in the pass band and an attenuation of more than 23 dB in the center frequency (450 Hz and 550 Hz) of adjacent DBFs; (ii) a very short dead time equal to 5 ms, and (iii) an acceptable settling time of about 20 ms. Similar consideration can be done for DBFs with center frequencies different from 500 Hz.

As far as the (i) result is concerned, the non-ideal transition band means the presence of interference between adjacent filters that, obviously, affects the metrological performance of the proposed solution. This situation is sketched in Fig. 2b as regards harmonic groups $G_{g,9}$, $G_{g,10}$ and $G_{g,11}$, considering three 6th order DBFs with center frequencies of 450 Hz, 500 Hz, 550 Hz, respectively. In the next section it will be shown that this aspect can be characterized and suitably compensated in order to allow complete compliance with the accuracy requirement of IEC standard [4]. Even in this case, similar consideration can be done for DBFs with different center frequencies.

Table 2. Dead time and settling time for DBFs with different orders, all centered at 500 Hz.

| | BROAD FILTER ORDER | | | | | |
|---|---|---|---|---|---|---|
| | 4 | 6 | 8 | 10 | 20 | 50 |
| DEAD TIME[1] [ms] | 2 | 5 | 10 | 14 | 37 | 107 |
| SETTLING TIME[2] [ms] | 21 | 23 | 33 | 38 | 64 | 158 |

[1] defined by the time it takes for the filter to change its response of from 0 to 10%.
[2] defined by the time it takes for the filter to settle within a regime value with a tolerance of ±5%.

## 4. DIGITAL FILTER CHARACTERIZATION IN A SIMULATED ENVIRONMENT

To evaluate the metrological performance of DBF and to compare it with the one furnished by the FFT approach, a suitable simulation stage has been designed in Matlab® 7 environment. Reference signals to be adopted as a test set were generated. Considering the main standards concerning the electromagnetic emission limits [3, 4, 29], four test sets were considered:

A purely sinusoidal signals at the fundamental frequency (50 Hz);

B signals at the fundamental frequency with harmonics up to the fifteenth, applied one at a time;

C signals containing the fundamental frequency with all the harmonics, up to a specified order;

D equal to test set C, with the addition of interharmonic components.

In all the considered test sets, frequency deviations within ± 5% of the nominal frequency value were applied to the realized waveform. Several amplitudes were considered for fundamental frequency, harmonics, and interharmonics according to the previously mentioned standards. Most cases consider a RMS amplitude equal to 220 V for the fundamental frequency, 10 V and 5 V for harmonic and interharmonic RMSs respectively. The sampling frequency was set equal to 4 kS/s and the analysis was conducted up to the 39th harmonic. In order to fix the minimum hardware requirements of the DAS (Data Acquisition System) to be adopted, all tests were realized evaluating also the sensitivity of the proposed DBF approach to the ENOB (Effective Number of Bits). In particular values of ENOB varying from 6 to 9 were considered.

Suitable figures of merit were introduced to estimate the filter responses:

1. RMSerr %, defined as the percentage relative difference between the imposed ($RMS_i$) and the estimated ($RMS_e$) RMS values of the considered signal:
$$RMSerr\% = \text{abs}\left(100 \times \frac{RMS_i - RMS_e}{RMS_i}\right) \text{ where: } RMS_e = \sqrt{\sum_{i=1}^{40} G_{g,ne}^2} \text{ where } G_{g,ne}$$
are the estimated harmonic group values.
2. THDGerr defined as the difference between the imposed ($THDG_i$) and the estimated ($THDG_e$) group total harmonic distortion values of the considered signal: $THDGerr = \text{abs}(THDG_i - THDG_e)$.

At first the RMSerr % related to the estimation of each group and due to the interference caused by adjacent filters was estimated. A number of sinusoidal signals of equal amplitude located at the fundamental and harmonic frequencies have been considered one by one. Figure 3 shows the RMSerr% estimation for each harmonic group. It is possible to highlight as the $G_{g,1}$ and $G_{g,39}$ groups are characterized by a very good RMSerr% estimate while other groups present errors near 3%. $G_{g,2}$ and $G_{g,38}$ groups show the worst performance with errors near to 4.5%. The different behaviors of groups $G_{g,1}$, $G_{g,2}$, $G_{g,38}$, $G_{g,39}$, are due to the unsymmetrical contributions of adjacent groups. By the estimation of these errors, suitable correction coefficients for each considered harmonic group were obtained and an online correction procedure was implemented. Figure 3 shows the estimated new mean RMSerr % after the correction procedure: it is possible to highlight the very good performance obtained with a maximum error lower than 0.3% and a mean error lower than 0.05%. After the development of this suitable correction procedure many additional tests were executed.

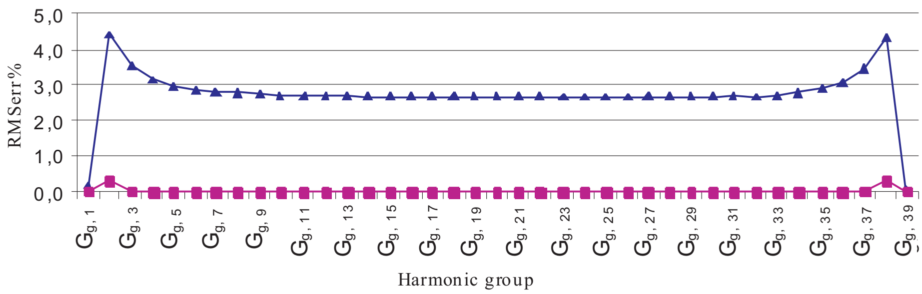


Fig. 3. RMSerr % before (▲) and after (■) correction.

For the sake of brevity only some results are reported in the paper. Figure 4 shows a performance comparison in terms of RMSerr % between the proposed corrected/uncorrected DBF solution and the synchronized FFT. Different signals, belonging to test set A, B, and C, are shown; they are measured with an ENOB equal to 8 and are characterized by different number and amplitude of harmonics. The obtained results show that: (i) corrected DBF gives responses very similar to those obtained by the synchronized FFT approach; (ii) even using test signals with very different harmonic content, the developed correction procedure has confirmed its suitability allowing a mean reduction of the RMSerr % from 0.24% to 0.05%.

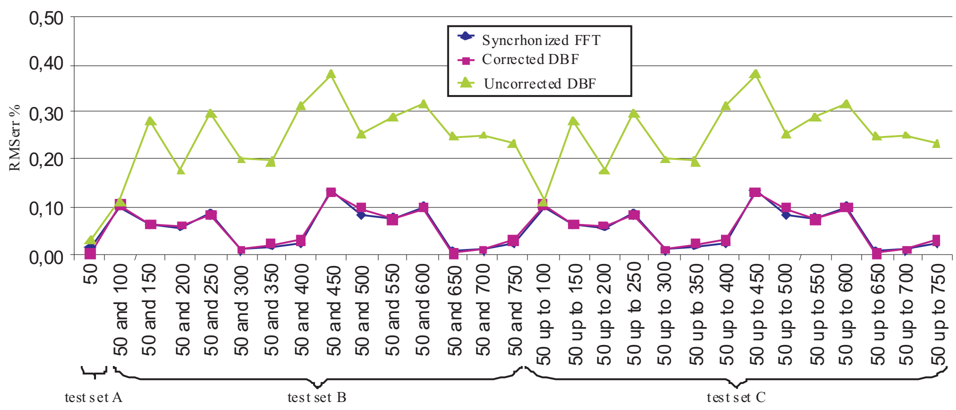


Fig. 4. Performance comparison respect RMSerr % between the proposed corrected/uncorrected DBF solution and synchronized FFT.

Table 3. Estimated RMSerr % versus ENOB and frequency deviation for two signals belonging to test sets C and D: DBF and FFT approaches are considered.

| TEST SIGNAL | FUNDAMENTAL FREQUENCY [Hz] | ENOB | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | 6 BIT | | 7 BIT | | 8 BIT | | 9 BIT | |
| | | DBF | FFT | DBF | FFT | DBF | FFT | DBF | FFT |
| 1st and 3th harmonics (C test set) | 50 synchronized | 0.143 | 0.141 | 0.024 | 0.021 | 0.064 | 0.061 | 0.046 | 0.043 |
| | 50.1 | 0.018 | 0.016 | 0.037 | 0.041 | 0.072 | 0.053 | 0.087 | 0.061 |
| | 50.5 | 0.223 | 0.088 | 0.156 | 0.036 | 0.141 | 0.020 | 0.133 | 0.015 |
| | 51 | 0.634 | 0.098 | 0.625 | 0.052 | 0.602 | 0.035 | 0.604 | 0.030 |
| | 51.5 | 0.452 | 0.117 | 0.483 | 0.066 | 0.483 | 0.049 | 0.491 | 0.044 |
| | 52 | 0.094 | 0.105 | 0.119 | 0.103 | 0.133 | 0.075 | 0.154 | 0.060 |
| | 52.5 | 0.158 | 0.136 | 0.132 | 0.109 | 0.099 | 0.077 | 0.101 | 0.080 |
| 1st and odd harmonics up to 15th and their interharmonics (D test set) | 50 synchronized | 0.093 | 0.091 | 0.035 | 0.032 | 0.037 | 0.035 | 0.002 | 0.001 |
| | 50.1 | 0.073 | 0.077 | 0.092 | 0.096 | 0.058 | 0.051 | 0.051 | 0.059 |
| | 50.5 | 0.069 | 0.002 | 0.059 | 0.016 | 0.118 | 0.028 | 0.083 | 0.019 |
| | 51 | 0.586 | 0.051 | 0.537 | 0.018 | 0.589 | 0.063 | 0.584 | 0.054 |
| | 51.5 | 0.507 | 0.087 | 0.519 | 0.071 | 0.468 | 0.115 | 0.492 | 0.106 |
| | 52 | 0.091 | 0.156 | 0.165 | 0.105 | 0.081 | 0.164 | 0.132 | 0.125 |
| | 52.5 | 0.079 | 0.134 | 0.073 | 0.128 | 0.087 | 0.145 | 0.100 | 0.155 |

Table 3 shows the RMSerr % for different ENOBs for two signals belonging to C and D test sets. Frequency deviations applied to fundamental and harmonics are also considered. The obtained values are then compared with those furnished by a non-synchronized FFT, as expected in the IEC 61000-4-7 standard. It is possible to highlight that: (i) in all the tests both DBF and FFT approaches lead to very good results in agreement with those required by the IEC 61000-4-7 (see Table 1 for comparison); (b) as expected, both DBF and FFT performance improves when the ENOB value increases (however, an ENOB value equal to 6 already furnishes good results); (c) DBF approach got good stability versus frequency deviation, while there are some particular deviation values (e.g. 51 Hz and 51.5 Hz) that deeply influence non-synchronized FFT performance.

The last simulation tests were concerned with the analysis of the DBF performance for the THDG estimation.

Table 4. THDGerr versus frequency deviation for signals belonging to test sets A, B and C: DBF and FFT approaches are considered.

| TEST SET | IMPOSED THDG | FUNDAMENTAL FREQUENCY | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | 50 Hz (synchronized) | | 50.5 Hz | | 51.5 Hz | | 52.5 Hz | |
| | | DBF | FFT | DBF | FFT | DBF | FFT | DBF | FFT |
| A | 0 | –0.033 | –0.003 | –0.035 | –0.045 | –0.039 | –0.122 | –0.043 | –0.096 |
| B | 0.05 | –0.010 | 0.000 | –0.011 | –0.015 | –0.013 | –0.079 | –0.016 | –0.056 |
| C | | –0.010 | 0.000 | –0.011 | –0.017 | –0.015 | –0.081 | –0.018 | –0.054 |
| B | 0.1 | –0.006 | 0.000 | –0.006 | –0.007 | –0.007 | –0.054 | –0.009 | –0.035 |
| C | | –0.005 | 0.000 | –0.006 | –0.009 | –0.011 | –0.056 | –0.015 | –0.031 |
| B | 0.2 | –0.005 | –0.002 | –0.003 | –0.003 | –0.004 | –0.031 | –0.005 | –0.019 |
| C | | –0.002 | 0.001 | –0.004 | –0.004 | –0.012 | –0.032 | –0.017 | –0.010 |
| B | 0.3 | 0.000 | 0.002 | –0.002 | –0.001 | –0.002 | –0.021 | –0.003 | –0.013 |
| C | | –0.002 | –0.001 | –0.003 | –0.002 | –0.015 | –0.022 | –0.021 | 0.000 |

Table 4 shows the THDGerr for different harmonic contents for some signals belonging to A, B, and C test set; a frequency deviation applied to the fundamental frequency was also considered.

The same consideration made for Table 3 can be applied. In addition, it is possible to highlight that: (i) both FFT and DBF performance improvement does not depend on the test set applied but only on the imposed THDG; (ii) the proposed DBF approach leads to worse performance for low values of THDG; (iii) both FFT and DBF performance improves if THDG increases.

## 5. DIGITAL FILTER PERFORMANCE ON EMULATED SIGNALS

An emulation stage has been designed and executed with the aim of assessing the performance of the optimized DBF approach in the presence of a real DAS, real operating conditions, and power quality disturbances very similar to the real ones. It was carried out following the specification given by the standards referenced in [3, 4, 28, 29] and comparing the obtained results to those furnished by the FFT based measurement algorithm.

Starting from the past experience documented in [21–27], a suitable measurement station, sketched in Fig. 5, has been set-up. It includes: (i) a processing and control unit, namely a personal computer (PC); (ii) eight Agilent TechnologiesTM 33120A function generators with arbitrary personalities (GEN 1, … ,GEN 8); (iii) a multiplexed eight channel ADC with 8 bits vertical resolution equipped with RS232 serial port interface. All the function generators are suitably inter-clocked and synchronized in order to output eight stable reference voltage waveforms (emulating the 4 voltages and 4 currents of a three phase system with neutral). The PC acts as a bus controller, uploads test signals in the RAM memory of function generators, acquires the data from the ADC by means of two serial RS232 ports and performs FFT and DBF based measurement algorithms.

According to ADC specifications, suitable low power signals, with an amplitude inside the [0–5] V range, have been emulated. The use of emulated signals instead of real ones is not a limitation in the metrological assessment of the proposed DBF-based measurement method, since the IEC 61000-4-7 standard imposes precise accuracy requirements for the power quality measurement instrument apart from the transducers (Table 1). The same reference signals and operating conditions adopted in the simulation stage were adopted. Some test results are reported in the following concerning the use of signals belonging to the A, B, and C test sets.

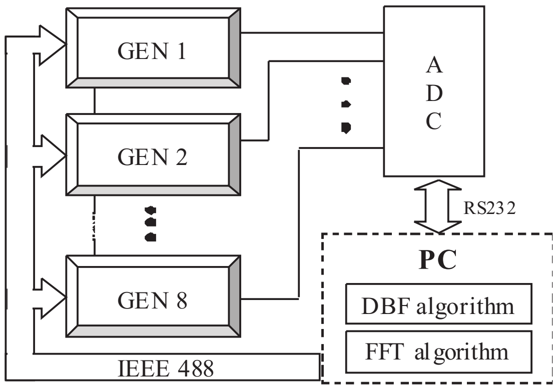


Fig. 5. The developed measurement station.

With the aim of establishing the DBF-based method reliability when frequency deviations are present, many tests were executed using sinusoidal signals in the [47.5–52.5] Hz range. Figure 6 reports the comparison between non-synchronized FFT and DBF outcomes for a frequency deviation in the [50–52.5] Hz range. It is possible to underline that:

– the FFT approach gives a RMSerr % about equal to zero for a 50 Hz signal, since it operates in ideal conditions and only the digital ADC vertical resolution takes effect; these conditions are reached every time the synchronization procedure, expected in the 61000-4-7 standard, suitably modifies the sampling frequency in function of the signal frequency;
- digital filter responses are quite constant and always acceptable, in function of the considered frequency deviations of the stimulating signal;
– non-synchronized FFT results depend on the applied frequency deviation; it is important to remark that IEC standard [4] clearly imposes a synchronization process before the application of the FFT estimation; loss of synchronization may cause errors in the calculated spectral line. However, the computational burden related to this synchronization process is heavy and often raises costs of measurement stations for PQ assessment [7].

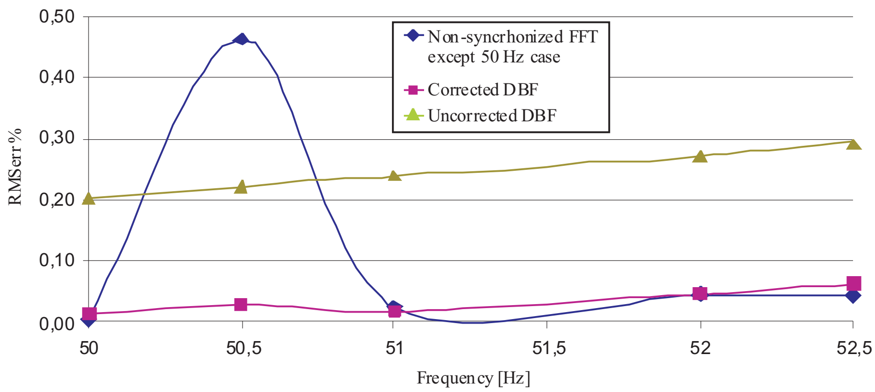


Fig. 6. Comparison of digital filter and FFT based measurement performance, in term of RMSerr %, for some signals belonging to the A test set when frequency deviations are present.

The comparison reported in Fig. 6 proves that digital filters are better than FFT in tolerating synchronization loss. In addition, Fig. 6 also shows the estimated RMSerr % before the correction procedure, thus highlighting the advantage of the correction procedure also with emulated signals.

For the sake of brevity, Fig. 7 reports some analyses concerning A, B, and C test sets. It is possible to highlight that both FFT- and DBF-based methods exhibit good behavior with RMSerr % always lower than 0.4% (much lower than the requirements of IEC standard [4]); also in these cases the correction procedure significantly improves the uncorrected DBF estimation.

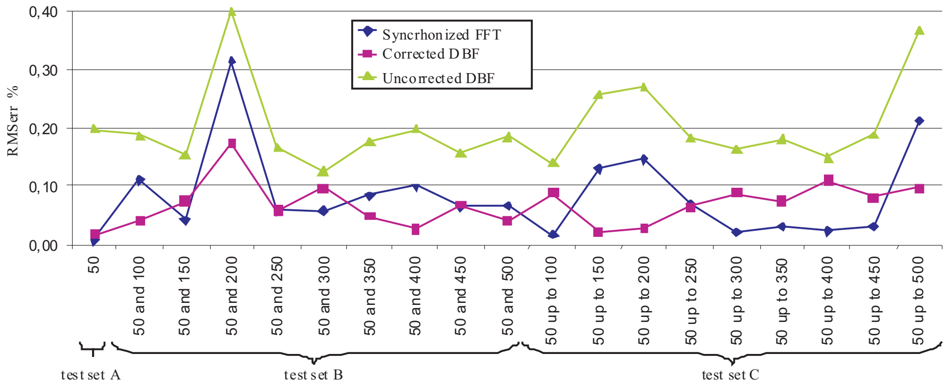


Fig. 7. Performance comparison respect RMSerr % between the proposed corrected/uncorrected DBF solution and synchronized FFT.

## 6. CONCLUSIONS

Steps of a research activity aimed at the realization of a cost-effective FPGA-based meter for power quality assessment have been reported. Attention has been paid to the measurement algorithm to be adopted. Digital filters shaped on the harmonic group, Broad Filter (DBF), have been optimized thoroughly for grouping measurements required by IEC EN 61000-4-7 standard.

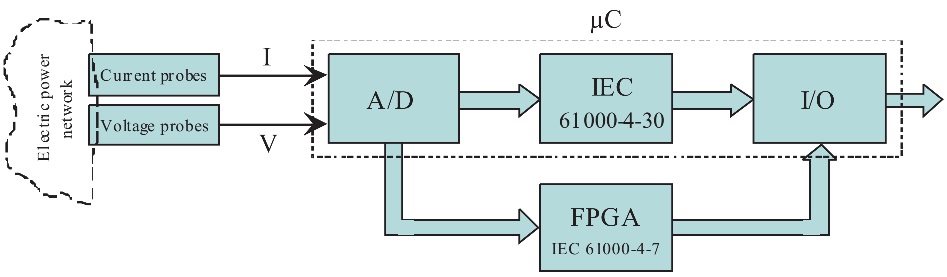


Fig. 8. The proposed measurement architecture.

A number of tests conducted on simulated and emulated signals shown as the proposed DBFs approach provide a good trade-off among accuracy requirements, computational burden and stability with respect to frequency deviations. A suitable calibration procedure allowed complete compliance with the metrological performance required by IEC 61000-4-7.

The executed performance comparison with a FFT-based solution allows asserting that the proposed approach can be seen as promising in the use of an alternative measurement approach with respect to the FFT one.

Although the simulated and experimental tests were focused on the harmonic group analysis, the obtained results can be easily extended to the analysis of interharmonic group, harmonic/interharmonic subgroup and to the components in signals with frequencies exceeding the harmonic frequency range (from 2 kHz to 9 kHz).

In fact, the analysis of these other parameters means the development of further DBFs with different bandwidth (e.g. 40 Hz for the interharmonic group or 200 Hz for the components above the harmonic frequency range). Obviously, these new DBFs have to be optimized with respect to these new goals.

The parallelism of filter bank calculations might be well suited with modern parallel processing such as that furnished by FPGA devices.

For these reasons, starting from the results reported in this paper, a measurement solution has been developed and proposed in [30]. The basic idea is shown in Fig. 8: a Data Acquisition System (DAS) of a common microcontroller allows the digitalization of the eight signals coming from current and voltage probes and the transmission of the digital samples to the FPGA inputs. At this stage: (i) the microcontroller allows evaluation of the power quality parameters suggested by [3] (i.e. interruptions, dips, sags, swells, and so on), where a smaller computational burden is required; (ii) the FPGA, as required by [4], allows harmonic and interharmonic measurement by using the proposed DBF solution. Finally, the obtained PQ measurements are stored and sent to the communication interface (I/O). The metrological performance of the proposed cost-effective PQ meter is going to be assessed both with emulated signals that in comparison with competitive solutions on real case studies.

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