# A Study on the Feasibility and Effectiveness of Digital Filters Approach for Power Quality Monitoring in Compliance with IEC 61000-4-7

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*Abstract-* Large scale monitoring of power quality in electrical apparatuses is nowadays a pressing need due to the liberalization of electrical market and the deeper interconnections of electrical networks. Many instruments are today available on the market. Even if they grant good accuracy and measurement capability, they are generally developed for single point measurements. Their use in large scale monitoring leads to high costs. These costs are also due to the accurate processing tasks they shall realize. 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 alternative measurement approach respect to the FFT one is proposed. Digital filters tuned on the single spectral line, and digital filters shaped on the harmonic group are optimized thoroughly for grouping measurements required by IEC EN 61000-4-7 standard. The obtained results allowing promising development in the use of this approach.

## I.     Introduction

In the electrical distribution the interaction between the load and the network supply may cause small or significant deviations from ideal current/voltage waveform. In Power Quality (PQ) the different aspects of these disturbances are enveloped [1]. Nowadays the interest towards the study of PQ disturbances is increasing continuously. This is particularly due to: (i) the deeper interconnection of electric networks, (ii) the less tolerance of equipments to voltage disturbances and, (iii) the increased awareness of the detrimental effects of poor quality translatable also in economic costs.

Whereas in the past, PQ was often seen as an implicit duty of system operators, today, with the liberalization of energy markets, 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 been defined, or have been 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 an important feature of meeting PQ targets that the interested parties agree on the method of gathering and presenting estimated data. For these reasons standards [2]-[8] regulate PQ disturbances by the means of suitable indices. Monitoring the electric system according to these standards gives the chance to improve the relationship among the electric markets' actors.

Two main categories of PQ disturbances can be introduced: variations and events [1], belonging respectively to steady state and transient phenomena. 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 [8]. 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 specifications of instruments shall state the range of uncertainty caused by all influence factors including the non-stationary characteristic of the signal, the aliasing phenomenon and the loss of synchronization.

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 Means Square) value.

Other useful solutions proposed to PQ monitoring are based on the use of digital filters [16]-[20]: different approaches are used depending on the type and architecture of digital filter as well as the power quality disturbances that are able to estimate.

Although the number of methods presented in the published papers 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 [8] and low cost are considered.

The processing and memory capabilities related to synchronization and FFT analysis required by the compliance with [7] and [8], deliver some issues that may limit the cost effective of the measurement solutions present on the market. In order to make clear these aspects let it consider a polyphase system with neutral wire, where 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) its 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.

The authors, starting from their past experience in this field [21]-[26], propose a study of the feasibility of digital filter approaches to monitor harmonic and interharmonic distortions, according to [8]. A number of digital filters, characterized by different types, architectures and order, was considered and optimized. Effectiveness of the chosen solution was confirmed by both the analysis of the digital filter response and its comparison with the FFT approach. Tests were made on more than thousand of simulated signals with typical harmonics and interharmonics disturbances.

## II. Theoretical background

Waveform distortion disturbance on power line is defined as the deviation of the signal from the perfect sinusoid. In order to monitor this disturbance, instruments able to measure spectral components, which are superimposed on the fundamental of the power supply systems at 50 Hz and 60 Hz, have to be used.

Since the need of having reference instruments with reproducible results irrespective of the characteristics of the input signals, the standard referenced in [8] describes functions and structure of the measuring instruments for waveform distortion analysis. For practical considerations, this standard distinguishes between harmonics, interharmonics and other components above the harmonic frequency range, up to 9 kHz. Harmonics are spectral components with a frequency (harmonic frequency) which is an integer multiple of the power supply (fundamental) frequency. Interharmonics are spectral components with a frequency between two consecutive harmonic frequencies. 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). Because the measurement of these last spectral components it is not an issue, in the following only harmonic and interharmonic analysis will be explained in detail.

In the assessment of harmonics and interharmonics, each spectral component shall be measured with a frequency resolution of 5 Hz and an observation period equal to 200 ms shall be considered. As suggested by [8], spectral lines have to be suitable grouped in order to obtain desiderated harmonic and interharmonic evaluations. This task provides an overall value, which includes the effects of fluctuations of the harmonic components.

The harmonic group is evaluated, for a 50 Hz system, by the sum of squared spectral lines in the +/-25 Hz interval respect the considered harmonic frequency (Equation 1). The interharmonic group is estimated by the sum of squared spectral lines between two consecutive harmonic components, according to Equation 2.

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

$$C_{ig,n}^2 = \sum_{i=1}^{9} C_{k+i}^2 \qquad \text{(Equation 2)}$$

In these equations: (i) $C_{k+i}$ is the RMS value of the spectral component located at the (k+i*5) Hz frequency and k is n times the fundamental frequency (harmonic frequency), (ii) $G_{g,n}$ is the resulting RMS value of the n-th harmonic group, and (iii) Cig,n is the RMS value of the n-th interharmonic group between the harmonic orders n and n+1.

In [8], the general structure of a reference instrument is given. It considers an FFT approach to estimate
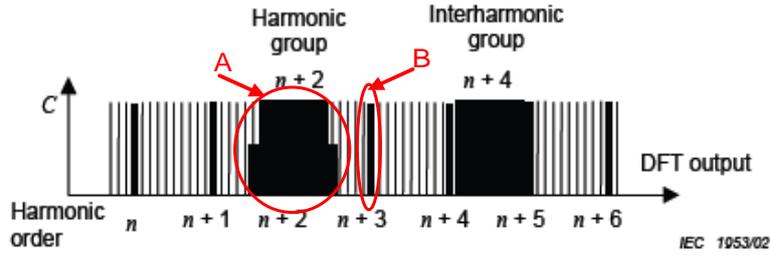
Fig. 1 Illustration of harmonic and interharmonic groups

spectral lines. This choice imposes the need of an accurate synchronization to avoid spectral leakage troubles. As mentioned above, [8] 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 grouping process acts as a digital filter placed on signal spectral components. Starting from this consideration in the following the adoption of a new measurement architecture that uses proper filter banks is proposed.

### III. The proposed digital filters approach

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

As far as the operating is concerned, filters may be developed for different purposes. Harmonic and interharmonic assessments, THD evaluation, frequency and event detections are important issues that have to be pursued as accurately as possible. In this study the harmonic group estimation is considered and filters settled for the above defined $G_{g,n}$ coefficients assessment are developed and made operative.

Starting from that reported in Section II, two architectures of digital filters could be used to achieve the required frequency decomposition: (i) filters tuned on single spectral line, here in after PIN FILTER, and (ii) filters shaped on harmonic group (here in after BROAD FILTER). 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 50 Hz, which is the breadth of harmonic groups. Fig. 1 sketches an example for both the shape of BROAD FILTER (highlighted as part A) and PIN FILTER (highlighted as part B). It can be highlighted that the estimate of the RMS of BROAD FILTERs output gives the above defined $G_{g,n}$ value; a suitable grouping procedure on the considered spectral lines has to be realized to obtain the desiderated values if a PIN FILTER is accounted for. In addition, for each harmonic group, eleven PIN FILTERs have to be combined, while only one BROAD filter has to be set.

Two types of digital filters were considered for both BROAD and PIN architectures: Finite Impulse Response (FIR) and Infinite Impulse Response (IIR) filter. At the former class belong filters as Equiripple, Interpolated Fir, etc., while in the latter are Butterworth, Chebyshev, Elliptic, Maximally Flat, etc. Fixed the architecture and type of the filter, several orders, capable to find a compromise between the required metrological performance and a feasible implementation, were considered.

In order to adjust all these parameters a simulation stage was arranged in Matlab® 7 environment. Reference signals to be adopted as test set were generated. Considering standards reported in [3]-[8] four main test sets were considered. In the first one, (A), there are purely sinusoidal signals at the fundamental frequency (50 Hz). The second test set, (B), contains signals at the fundamental frequency added with its harmonics up to the fifteenth applied one at once. Signals containing the fundamental frequency added with its entire harmonic applied in progressive manner fall in the third test set (C). The further addition of interharmonic components characterizes the D class respect to the previous ones. In the entire proposed test set frequency deviations within +/- 5% of the nominal frequency value were applied to the realized waveform. Several amplitudes were considered for the fundamental frequency, the harmonics and the related interharmonics. The most of the cases consider a RMS
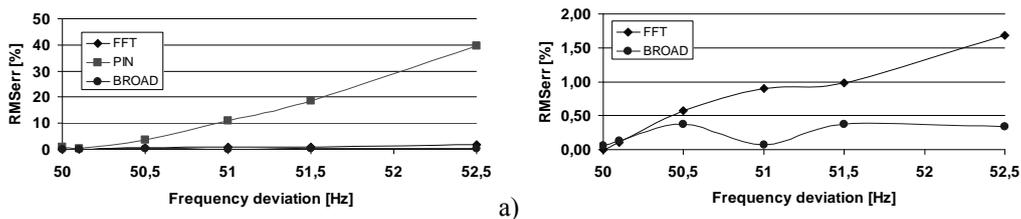


Figure 2 (a) Comparison of BROAD, PIN and FFT performance, in term of RMSerr, for some signals belonging to the A test set; (b) highlighting of FFT and BROAD results.

amplitude equal to 220 V for the fundamental frequency and 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 40$^{TH}$ harmonic. All the considered test sets, architectures, types and orders of filters compose a set of more than one thousand case studies.

Suitable figures of merit were introduced to estimate filter responses:

1) RMSerr, defined as the percentage error between the imposed (RMScs) and the estimated (*RMSf*) RMS values of the considered signal:

$$RMSerr = abs\left(100 \text{ x } \frac{RMScs - RMSf}{RMScs}\right) \text{ where } RMScs = \sqrt{\sum_{i=1}^{40} Gcs_i^2} \text{ and } RMSf = \sqrt{\sum_{i=1}^{40} Gf_i^2} \text{ ;}$$

$Gcs_i$ and $Gf_i$ are the imposed and estimated harmonic group values.

2) ΔTIME and ΣTIME respectively defined as the time the filter requires to detect an event, and the time to provide a 99% steady state response after the detection time.

3) BURDEN and MEM respectively defined as the number of additions and multiplications required by the filter and the total samples to be preserved in memory to compute the response.

An optimization stage executed on a number of tests varying filters architecture, type and order showed that:

(i) IIR filters grant a compromise between computational burden and metrological accuracy;

(ii) among IIR filters the Butterworth one is characterized by acceptable performance even if the order of the filter is quite low;

(iii) BROAD filters of order equal to six allow good stability, good metrological performance and reduced computational time;

(iv) different orders are required for PIN filters solution; a minimum order equal to two is needed for the harmonic estimation, while orders up to fourteen are required for the side spectral lines.

For the sake of brevity, all steps of the optimization stage are not reported in the paper, while final outcomes are reported with more detail.

Some results concerning metrological performance of considered filters, estimated in terms of RMSerr, are given in the following. All the reported results are also compared with those furnished by traditional FFT approach with rectangular window.

Figure. 2a) reports results for some signals of the (A) test set when a frequency deviation is present. Figure. 2b) highlights the comparison between non synchronized FFT and BROAD filters outcomes.

It is possible to underline as: (i) the FFT approach gives out a RMSerr equal to zero for a 50 Hz signal, since it operates in its ideal conditions. These conditions are reached every time the synchronization procedure suitably modify the sampling frequency in function of the signal frequency; (ii) BROAD filters give better performance than PIN filters that in some case give unacceptable estimates; (iii) BROAD filters responses are quite constant and always acceptable, in function of the considered frequency deviations of stimulus signal; (iv) non synchronized FFT results strongly depend on the applied frequency deviation. It is important to remark that [8] clearly imposes a synchronization process before the application of the FFT estimation; the loss of synchronization may cause errors in the calculated spectral line. However, computational burden related to this synchronization process is heavy and often raises costs of measurement stations for PQ assessment. The comparison of Figure 2b) wants only to show better stability of BROAD filters than FFT approach versus the loss of synchronization

Some analyses concerning B) and C) test sets are respectively reported in Figure 3 a) and Figure 3b). It is possible to highlight as: PIN and BROAD filters outputs are almost constant versus the applied signals; both filters exhibits good behaviors; BROAD filters performance is two order better respect to
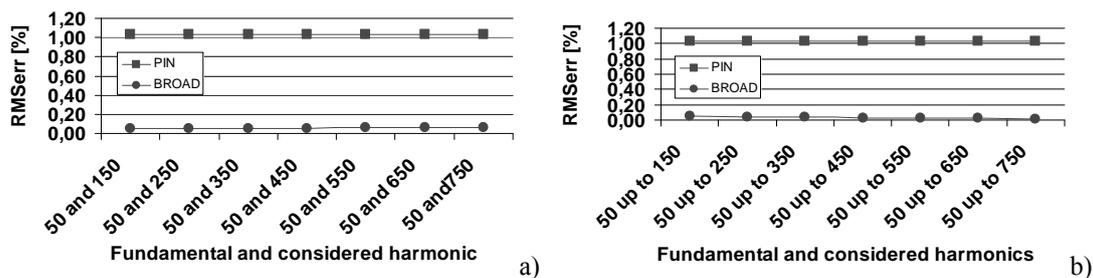


Figure 3 Comparison of BROAD and PIN filter performance, in term of RMSerr, for some signals belonging to the B (a) and C (b) test set.
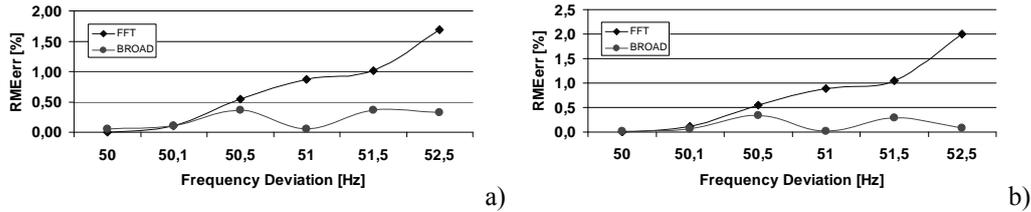
Figure 4 Comparison of BROAD and PIN filter performance, in term of RMSerr, for some signals belonging to the B (a) and C (b) test set when frequency deviations are present.

PIN ones. Estimates obtained by the FFT approach are not reported since the estimated RMSerr is equal to zero due the applied ideal conditions.

Different results are obtained when frequency deviation are considered. Figure 4 reports behaviors of RMSerr versus the frequency deviation for two of the cases proposed in Figure 3. The fundamental frequency and the third harmonic were considered in Figure 4a, while the fundamental frequency and all the odd harmonics up to the 15th were considered in Figure 4b). PIN filter are not reported since their RMSerr was very high if compared with BROAD and FFT approaches. Once again Broad filters show very good stability in spite of the shift from the ideal 50 Hz condition. Results obtained for the other cases of Figure 3 are very similar to those proposed in Figure. 4.

Figure 5 reports results for signals belonging to the D) test set. In particular, the first case of Figure 5a) considers the fundamental frequency and all its interharmonics within the +/-25 Hz range, while in other cases each harmonic (with its interharmonics) at time is added to the fundamental. Each case of Figure 5b) reports RMSerr for signals composed by the fundamental frequency with its interharmonics and all the harmonics (with their interharmonics) falling in the considered frequency interval. Obtained results show that: (i) PIN and BROAD filters give out to acceptable responses if compared with the FFT approach; (ii) PIN filters furnish better performance than BROAD ones increasing the weight of interharmonic contribution, however the maximum RMSerr for BROAD filters is always lower than 0.6%.

To fix the minimum hardware requirements of the DAS (Data Acquisition System) to be adopted in the realizing instrument further tests were carried out. Sensitivity of proposed filters approach to ENOB (Effective Number of Bits) was assessed.

Table I gives the estimated RMSerr versus two values of ENOB for two signals belonging to test sets C) and D) and several values of frequency deviation. The RMSerr figure of merit does not seem to be affected by vertical quantization for all the considered approaches. BROAD filters always give better values respect to PIN filters. BROAD filters estimates seem to be more stable versus the frequency deviation and grant very good outcomes if compared to non synchronized FFT results. Very similar estimates are obtained in the synchronized (50.0 Hz) cases where both methods give out errors lower than the error related to the selected ENOB.

As far as the ΔTIME figure of merit is concerned, a negligible time was noticed for optimized BROAD filters; a ΣTIME equal to 100 ms (5 periods of the fundamental 50 Hz frequency) was estimated to furnish a steady state response after an event detection;. PIN filters require about 100 ms (5 periods of the fundamental 50 Hz frequency) as ΔTIME and 1300 ms (65 periods of the fundamental 50 Hz frequency).

As for the BURDEN figure of merit BROAD filters require 9 real additions and 9 real multiplications to produce harmonic group output, while PIN filters need of 93 real additions and 93 real multiplications. Considering that 40 BROAD and 40 grouped PIN filters are required to analyzed up the 40th harmonic a total burden of 360 real additions and 360 real multiplications and 3720 real
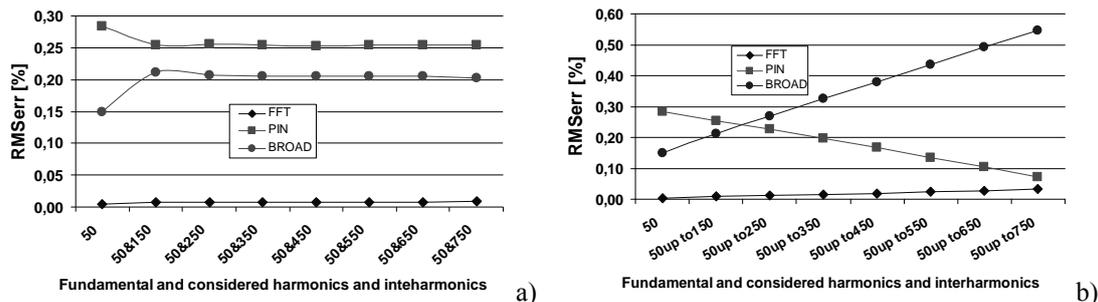


Figure 5 Comparison of BROAD, PIN and FFT performance, in term of RMSerr, for some signals belonging to the D test set.

additions and 3720 real multiplications are respectively required for the analysis of each phase. MEM related to BROAD filters is equal to six samples for each phase while PIN filters require up to 14 samples to be stored. The memory burden related to the filter coefficients wasn't considered since they can be preserved in lookup table placed in the ROM memory.

As far as the FFT approach is concerned, considering same conditions reported above, and a frequency resolution equal to 5 Hz, following performance should be achieved: (i) measurement results shall be updated within the required 200 ms (corresponding to ten periods for a 50 Hz system). This means that the whole 8 FFT should be calculated within 200ms; Since usually DSP or microcontrollers-based measurement systems are characterized by sequential operating, the above-mentioned requirements lead to a maximum time of 25 ms available to acquire and store the samples, compute and transmit each FFT result; (ii) for each one of the eight signal at least 800 samples should be acquired, stored and managed; (iii) each FFT calculation, performed on M (80) real samples, requires $M*log2(M)$ (7715) additions and $M*log2(M/2)$ (7715) multiplications. The required computational burden is very huge if compared to that provided by BROAD filters approach.

From the above reported considerations, according to all the considered figures of merit, can be highlighted that: (i) BROAD filters grant acceptable RMS errors respect the FFT approach. This is particularly true if the quantization effects are taken into account; (ii) BROAD filters show a lower computational burden than the FFT approach; (iii) the need of synchronization could be eliminated in the BROAD filters approach if little RMSerr are accepted; (iv) the steady state time response for BROAD filters imposes up to five period of flagged signals while this not occurs if a FFT processing is considered. For these reasons these digital filters seems to be promising for an alternative measurement approach respect to the FFT one.

Table I. Estimated RMSerr versus two values of ENOB for two signals belonging to test sets C) and D) and several values of frequency deviation.

|  | Freq Dev. [Hz] | 7 bit | | | 8 bit | | |
|---|---|---|---|---|---|---|---|
|  |  | FFT | PIN | BROAD | FFT | PIN | BROAD |
| 1 and 3 harmonics (C test set) | 50.0 | 0.20 | 1.24 | 0.25 | 0.27 | 1.31 | 0.33 |
|  | 50.1 | 0.11 | 0.41 | 0.11 | 0.15 | 0.37 | 0.07 |
|  | 50.5 | 0.59 | 3.63 | 0.35 | 0.61 | 3.64 | 0.33 |
|  | 51.0 | 0.89 | 11.00 | 0.03 | 0.90 | 11.00 | 0.02 |
|  | 51.5 | 1.09 | 18.50 | 0.36 | 1.00 | 18.60 | 0.32 |
|  | 52.5 | 1.71 | 39.52 | 0.30 | 1.73 | 39.49 | 0.30 |
| 1 and odd harmonics up to 15TH and their interharmonics (D test set) | 50.0 | 0.77 | 0.25 | 0.75 | 0.55 | 0.73 | 0.11 |
|  | 50.1 | 0.13 | 0.30 | 0.06 | 0.16 | 0.29 | 0.06 |
|  | 50.5 | 0.68 | 3.55 | 0.26 | 0.62 | 3.45 | 0.31 |
|  | 51.0 | 0.98 | 10.96 | 0.06 | 0.88 | 10.86 | 0.01 |
|  | 51.5 | 1.29 | 18.41 | 0.23 | 1.15 | 18.40 | 0.25 |
|  | 52.5 | 2.08 | 38.93 | 0.01 | 2.01 | 38.99 | 0.07 |

IV **Conclusions**

First steps taken in the framework of a research activity aimed at the realization of a cost-effective FPGA-based meter, for power quality assessment have been accounted for. The attention has, in particular, been paid to the measurement algorithm to be adopted. Digital Filter filters tuned on the single spectral line (PIN FILTER), and digital filters shaped on the harmonic group (BROAD FILTER) have been optimized thoroughly for grouping measurements required by IEC EN 61000-4-7 standard.

A number of tests conducted on simulated signals shown that BROAD filters grant better trade-off between computational burden and accuracy respect than PIN ones; For the optimized BROAD filters acceptable bias, good repeatability, and reasonable processing time have been experienced if compared with the usually applied FFT based approach thus allowing a promise in the use of alternative measurement approach respect to the FFT one. In addition the parallelism of filter bank calculations
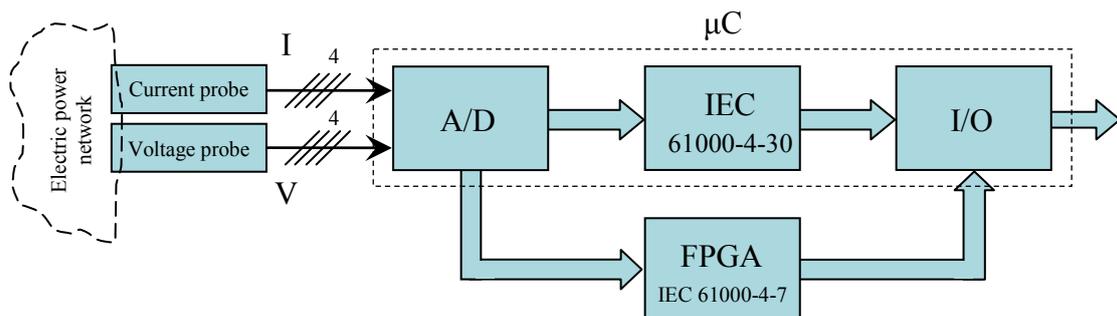


Figure 6. The proposed measurement architecture

might be well suited with modern parallel processing as those furnished by FPGA devices. A possible measurement solution is proposed in Figure 6. 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 evaluating of the power quality parameters suggested by [7] (i.e. interruptions, dips, sags, swells, and so on), where less computational burden is required; (ii) the FPGA, as required by [8], allows harmonic and interharmonic measurement by using the proposed digital BROAD filters solution. Finally, the obtained PQ measurements are stored and sent to the communication interface (I/O).

The ongoing research work will concern with: (i) the analysis of BROAD filter performance if interharmonic estimation is concerned; (ii) the set-up of an optimized FPGA-based measurement architecture; (iii) the choice and the characterization of measurement probes, and (iv) the comparison with competitive measurement solutions present on the market.

## References

[1]   M.H.J. Bollen, "Understanding Power Quality Problems: Voltage Sags and Interruptions", New York, IEEE Press, 1999.
[2]   Joint Working Group Cigrè C4.07/CIRED, 8-10 Oct. 2003, "Recommending Power Quality Indices and Objectives in the Context of an Open Electricity Market", *CIGRÈ/IEEE PES International Symposium on Quality and Security of Electric Power Delivery Systems.*
[3]   IEEE Standard 1159.3-2003, "IEEE Recommended Practice for Transfer of Power Quality Data".
[4]   IEEE Trial-Use Standard 1459-2000, "Definitions for the Measurement of Electric Power Quantities under Sinusoidal, Nonsinusoidal, Balanced, or Unbalanced Conditions".
[5]   IEEE Standard 1159-1995, "IEEE Recommended Practice for Monitoring Electric Power Quality".
[6]   IEEE Standard 519-1992, "IEEE Recommended Practices and Requirements for Harmonic Control in Electrical Power System".
[7]   International standard IEC 61000-4-30 "Electromagnetic Compatibility - Testing and Measurement Techniques – Power Quality Measurement Methods," 2003.
[8]   International standard IEC 61000-4-7 "Electromagnetic Compatibility - Testing and Measurement Techniques – General Guide on Harmonics and Interharmonics Measurements and Instrumentation, for Power Supply Systems and Equipment Connected thereto," 2002.
[9]   B. Perunicic, M. Mallini, Z. Wang, Y. Liu, "Power quality disturbance detection and classification using wavelets and artificial neural networks," *Proceedings of 8th International Conference on Harmonics And Quality of Power*, vol. 1, pp. 77 – 82, 1998.
[10] E. Styvaktakis, M. H. J. Bollen, I. Y. H. Gu, "Automatic Classification of Power System Events Using RMS Voltage Measurements," *Power Engineering Society Summer Meeting*, vol. 2, pp. 824-829, 2002
[11] A. M. Gaouda, S. H. Kanoun, M. M. A. Salama, A. Y. Chikhani, "Pattern Recognition Applications for Power System Disturbance Classification," *IEEE Trans. Power Del.*, vol. 17, no. 3, pp. 677-683, July 2002.
[12] Z. - L. Gaing, "Wavelet-based neural network for power quality disturbance recognition and classification," *IEEE Trans. Power Del.*, vol. 19, no. 4, pp. 1560-1568, Oct. 2004.
[13] M. Wang, G. I. Rowe, A. V. Manishev, "Classification of power quality events using optimal time-frequency representations, theory and application," *IEEE Trans. Power Del.*, vol. 19, no. 3, pp. 1496-1503, July 2004.
[14] F.-F. Zhu, G.-S. Hu, J. Xie, "Classification of power quality disturbances using wavelet and fuzzy support vector machines," *Proceedings of the 4th International Conference on Machine Learning and Cybernetics*, vol. 7, pp. 3981-3984, Aug. 2005.
[15] V. Matz, T. Radil, P. Ramos, A. C. Serra, "Automated Power Quality Monitoring System for On-line Detection and Classification of Disturbances," Proc. IMTC/2007, Warsaw, Poland, 2007.
[16] P.K. Dash, S.K. Panda, A.C. Liew, K.S. Lock, "A New Approach to Monitor Power Quality Problems in Power Supply Networks," *Proceedings of International Conference on Power Electronics and Drive Systems*, vol. 2, pp. 857 - 861, 1997.
[17] Z. Chen, P. Urwin, "Power Quality Detection and Classification Using Digital Filters," *Proc. Porto PowerTech*, vol. 1, Sep. 2001.
[18] F.R. Ramos, M.V. Ribeiro, J.M.T. Romano, C.A. Duque, "On Signal Processing Approach for Event Detection and Compression applied to Power Quality Evaluation", *10th International Conference on Harmonics and Quality of Power*, pp. 132-138, 2002.

[19]  M.A. Mostafa, "Kalman Filtering Algorithm For Electric Power Quality Analysis: Harmonics and Voltage Sags Problems", *Proceedings of LESCOPE/03*, pp. 110-119, 2003.

[20]  P.K. Dash, M.V. Chilukuri, "Hybrid S-Transform and Kalman Filtering Approach for Detection and Measurement of Short Duration Disturbances in Power Networks", *IEEE Transactions on Instrumentation and Measurement*, vol. 53, no. 2, pp. 588 - 596, April 2004.

[21]  G. Bucci, C. Landi, "On-line digital measurement for the quality analysis of power systems under nonsinusoidal conditions," IEEE Transaction on Instrumentation and Measurement, vol. 48, n. 4, pp. 853-857, 1999.

[22]  G. Bucci, E. Fiorucci, C. Landi, "Digital measurement station for power quality analysis in distributed environments," IEEE Transaction on Instrumentation and Measurement, vol. 52, n. 1, pp. 75-84, 2003.

[23]  A. Bernieri, L. Ferrigno, M. Laracca, P. Verde, "Wireless sensor network for power quality monitoring according to IEC 61000-4-30", Proc. of XIII IMEKO-TC4, vol. 2, pp. 752-758, 2004.

[24]  D. Castaldo, D. Gallo, C. Landi, A. Testa, "A digital instrument for nonstationary disturbance analysis in power lines," IEEE Transaction on Instrumentation and Measurement, vol. 53, n. 5, pp. 1353- 1361, 2004.

[25]  D. Gallo, C. Landi, R. Langella, A. Testa, "Implementation of a test system for advanced calibration and performance analysis of flickermeters," IEEE Transaction on Instrumentation and Measurement, vol. 53, n. 4, pp. 1078- 1085, 2004.

[26]  D. Gallo, C. Landi, N. Pasquino, "Design and Calibration of an Objective Flickermeter," IEEE Transaction on Instrumentation and Measurement, vol. 55, n. 6, pp. 2118-2125, 2006.