# A Virtual Instrument for the Electric Power Monitoring in the Distributing Network

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*Abstract* - This work proposes a virtual instrument (VI) for the electric power quality monitoring aiming to act in real-time for detecting, monitoring and recording all typical disturbances superimposed on the ideal signal; it is based on both IEC standards 61000-4-30 and 61000-4-7 [1] [2] and on the directive for the *Consultation of the Italian Authority for the Electric Power and Gas* of April 6, 2005. The latter presents the peculiar features of an experimental monitoring system for the mid voltage electric energy distribution network whose experimentation should lead the distributing companies to the respect of the Voltage Quality (VQ) monitoring obligation.

According to the above mentioned regulations, the proposed VI acquires both line voltage and current waveforms and carries out the innovating power quality indexes calculations in times comparable with those of other commercially available instruments; in order to obtain an accurate estimation of the parameters of interest a suitable Fast Fourier Transform interpolation algorithm is implemented in the VI. .

The laboratory prototype is based on a low cost data acquisition card equipped with suitable current and voltage sensors; the VI code is developed using National Instruments *LabVIEW*® Professional Development System and Mathworks *MATLAB*® and achieves very interesting performances.

**Keywords:** Power measurement, power quality, spectral analysis, harmonic analysis

## I.   Introduction

In the recent years there have been remarkable changes in the nature of electrical loads; electric and electronic appliances equipped with switching power supply units are now ubiquitous in domestic, office and industrial places; the main consequence of the growth of this kind of loads is the increase of the harmonic content of the power network and this leads to serious power quality issues for public networks. Recommendations have been issued by the standard organizations both to limit the injection of harmonics and to define the characteristic of voltage supplied by distributing companies [3]. Consequently, the power quality monitoring activity has gained a great importance in the last few years; this objective requires the definition of one or more power quality indexes as fair and wide accepted as possible. Unfortunately the already proposed power-quality indexes do not ensure the fulfilment of these objectives. In the authors' opinion, the use of a virtual instrument integrating all the data acquisition, processing, display and data recording tasks seems to be the right road to an economic, flexible and efficient power monitoring system.

The Italian Authority for the Electric Power and Gas (AEEG) with the deliberation no. 4 of January 30, 2004 (Integrated Text of Provisions of the Authority for the Electric Power and Gas as Regard Electric Power Distribution Service Quality, Measurement and Sale – Regulation Period 2004-2007) and following modifications and integrations introduced a new and important concept for final customers connected to the distribution network: **the Quality Contract**.

Thanks to this directive the distributing company can draw up a contract with final customers or other subjects like electric power facilities or interconnected distributing companies for minimum quality levels. In Italy the deregulation of the electric market has had a profound impact on both the electric power industry and its customers, opening up new prospects and requiring greater attention for power quality monitoring; this has been made possible thanks to the efforts of the AEEG too.

In the above-mentioned consultative document of april 6, 2005, the AEEG introduced the minimum features of a voltage quality monitoring system on middle voltage networks; this system has been prototyped and tested during 2005 by CESI S.p.a., an italian research center leader in testing and certification of electromechanical equipment and power system studies and consultancy.

Following the same approach, the AEEG also activated two other initiatives:

a) a sample monitoring campaign for the Italian Electric Power National Transmission Network (in collaboration with the Italian Transmission System Operator, deliberation n. 250/04);

b) the standardization of the voltage quality registration obligations between distribution and transmission; in the near future, this will lead to the extension of voltage quality (VQ) parameters registration obligations also to high voltage electric power distributing companies.

This approach paves the way to new and more complex instruments for power measurement and monitoring which will have to provide flexibility, expandability and high-speed performances.

## II.    Voltage quality and power quality indexes

For power quality assessment, the AEEG proposed the observation of the following parameters [1]:

*i)* source voltage amplitude fluctuations;
*ii)* source voltage interruptions;
*iii)* voltage holes;
*iv)* current and voltage harmonics;
*v)* short term ($P_{st}$) and long term ($P_{lt}$) flicker intensity;
*vi)* voltage lack of balance.

However, the previous parameters do not always ensure a full account of the power quality; in fact, following the results of independently made measurement experiences, several other National Energy Regulators have adopted definitions, limitations, and indicators that disagree with those given [1] and [2]; besides, these different approaches, combined with different network characteristics, makes both the analysis and the harmonization very hard.

Really, in the last few years, a lot of additional power quality indexes have been proposed by many authors; they, when compared with the limits of the previous ones, make it possible a more in-depth and careful analysis of the power quality state. This is the case, as an example, of the *distortion index* (DIN) that substitutes the *total harmonic distortion* (THD) [4]; this new parameter permits to overcome the problem of measurements on frequency modulated signals that do not have a fundamental component.

The instrument presented in this work measures and/or computes, beyond those indicated by the AEEG, an expanded set of power quality indexes that, in the authors' opinion, are important for a right evaluation of the electric power quality. The following indexes are computed from acquired data:

1.  the voltage/current distortion index ($DIN_V$ and $DIN_I$ respectively) defined as [5]:

$$DIN_V = \frac{\sqrt{\sum_{k=2}^{\infty}|v_k|^2}}{\sqrt{\sum_{k=1}^{\infty}|v_k|^2}}, \qquad\qquad DIN_I = \frac{\sqrt{\sum_{k=2}^{\infty}|i_k|^2}}{\sqrt{\sum_{k=1}^{\infty}|i_k|^2}}$$

being $|v_k|^2$ ($|i_k|^2$) the RMS values of the k$^{th}$ harmonics of voltage/current respectively.

2.  the generalized voltage/current distortion factors $GTHD_V$ and $GTHD_I$ given by

$$GTHD_V = \sqrt{\frac{U_\Sigma^2}{U_{\Sigma_1}^2} - 1} \qquad\qquad GTHD_I = \sqrt{\frac{I_\Sigma^2}{I_{\Sigma_1}^2} - 1}$$

where:
-    $U_\Sigma$ and $I_\Sigma$ are the voltage and current collective RMS values respectively, defined as:

$$U_\Sigma = \sqrt{\sum_{k=1}^{n}U_{L_k}^2} \qquad \text{and} \qquad I_\Sigma = \sqrt{\sum_{k=1}^{n}I_{L_k}^2}$$

being:

- $U_{L_k}$ and $I_{L_k}$ *(j = 1,2, ..., n)* the rms values of the zero-sum line voltages and the line current respectively;

- $U_{\Sigma_1}$ and $I_{\Sigma_1}$ the collective voltage/current RMS values of the fundamental components only of voltage and current respectively;

- *n* the number of phases of the power system.

3. the *generalized voltage/current distortion factor+*

$$GTHD_V^+ = \sqrt{\frac{U_\Sigma^2}{U_{\Sigma_{1+}}^2} - 1} \qquad\qquad GTHD_I^+ = \sqrt{\frac{I_\Sigma^2}{I_{\Sigma_{1+}}^2} - 1}$$

being $U_{\Sigma_{1+}}$ and $I_{\Sigma_{1+}}$ the collective positive sequence voltage/current RMS values of the fundamental components only of voltage and current respectively.

Indexes 2 and 3 are computed to obtain a quantification of both distortion and unbalance; a comparison between the values of $GTHD_V^+$ and $GTHD_V$ (or between $GTHD_I^+$ and $GTHD_I$) gives indication on what is the main cause of power quality (distortion or unbalance).

4. Coefficients $\eta$ and $\eta^+$:

$$\eta = \frac{GTHD_I}{GTHD_V} \qquad\qquad \eta^+ = \frac{GTHD_I^+}{GTHD_V^+}$$

which provide information about the location of the source producing distortion.

5. The *generalized active ($P_\Sigma$)* and *apparent power ($S_\Sigma$)* given by:

- $P_\Sigma = \int_0^T \sum_{k=1}^n u_{L_k}(t) \cdot i_{L_k}(t)\,dt$ (*T* is the period of the voltage and current waveforms);

- $S_\Sigma = U_\Sigma \cdot I_\Sigma$;

6. The *generalized power factor* $\lambda = \dfrac{P_\Sigma}{S_\Sigma}$ ;

7. The *supply and loading quality index* $\xi_{slq} = \dfrac{P_\Sigma}{P_{\Sigma_{+1}}}$

which gives information about the major source of distortion/unbalance:

- $\xi_{slq} > 1$ when the distortion and/or unbalancing effects of the supply prevail over the load distorting and unbalancing effects:
- $\xi_{slq} < 1$ when the load distorting and/or unbalancing effects prevail over the supply voltage distortion and/or unbalance;

8. *the harmonic global index* $\xi_{HGI} = \dfrac{\left\lVert I_{\Sigma_L} \right\rVert^2}{\left\lVert I_{\Sigma_S} \right\rVert^2}$ ,

where

- $I_{\Sigma_L}$ is a vector whose components are the collective RMS values of the harmonic and sequence components associated with active powers reflected backward from the load to the source;
- $I_{\Sigma_S}$ is a vector whose components are the collective RMS values of the harmonic and sequence components associated with active powers flowing from the source towards the load.

9. the *k-factor* of every phase [6] which is a weighting of the harmonic load currents according to their effects on transformer heating.

However, for the most part of these new indexes, there are not available precise rules of use; this is mainly due to the novelty of them and, consequently, to the absence of pre-established limits. Finally, it is worth underling that the critical part of question is the implementation of a both *on-line hard real time* and *accurate* estimation algorithm.

## III. Measuring system

The design of the measurement system has been made in many steps; first of all a trial version of the *VI* was developed to verify both the involved models and algorithms using numerically synthesized corrupted signals. This simulation *VI* has been developed with the aim to precisely simulate a three-phase system behavior. The final objective of this phase was to see if the developed algorithm was able to discover all the power source imperfections that, thanks to the great care of the simulation, can be finely controlled by the operator.

In the simulation three current and voltage waveforms were numerically generated superimposing to the theoretical ones all the disturbances defined in the CEI EN 50160 Standard [3]: interrupts, voltage holes, overvoltages, flicker, harmonics up to 40th, inter-harmonics and noise. Then, after results verification, the techniques relevant to both acquisition and optimization of signals have been developed to obtain *real-time* measurements. Encouraged by the simulation results, a prototype system useful to both monitor and analyze the power quality in three-phase systems has been implemented on a Pentium IV personal computer with 2.4 GHz clock, 1 GBytes of RAM equipped with an eight channel simultaneous sampling analog-to-digital conversion board with 14 bit resolution at a maximum sampling rate of 2.5 MSample/s (National Instrument PCI-6133 DAQ [7]). Real current and voltage waveforms of the monitored three-phase system have been acquired using Hall effect-based transducers chosen with bandwidth equal to 100 kHz, linearity of 0.1% and having a delay time less than 1 μs.

### III.A   The instrument performances

For a quantitative evaluation of the measurement uncertainties the AEEG proposes to use TeamWare's *Wally-RTU Electric power quality station* [8]; it is a three-phase power quality analyzer which accomplishes voltage, current, frequency, harmonic distortion and electrical energy consumption measurements; it has a sampling frequency of 6.4 kSample/s and uses a phase locked synchronous real-time sampling technique, is declared *class A* instrument whit regard to methodology and *class B* instrument with regard to uncertainty results. Really, it gives an uncertainty less than 0.5 % for input values ≥ 10% FS (full scale input), and less than 1% when the input signal varies in the range 1-10 % of FS. It is important to note that the measurement bandwidth of this instrument does not comply with the IEC 61000-4-7 minimum bandwidth requirements, which is at least 9 kHz. The maximum sampling rate of the DAQ card used in this project is greatly over the requirements for the particular application; the actual sampling rate used for the presented VI was 40.96 kSample/s and this ensures a total uncertainty less than 0.5% for input values ranging 1-20 % FS and below 0.1% for signals of 20% FS and over. The realized power quality monitoring device prototype measures and shows besides the measurements required by the AEEG all the indexes defined in section II.

All the measurements made by the VI in a 10 minutes wide aggregation window (as established in [3]) are recorded on files; even the disturbances (interrupts, voltage holes and over voltages) are recorded on suitable files in a real-time basis. Moreover, the presence of the recording files permits to create an archive containing all the information with regard to the electric power quality evolution. Even if it is not specifically requested by the AEEG, the instrument monitors the over voltages which are significant for voltage quality. To obtain the real-time elaboration of acquired data, the aggregation window is subdivided in many subintervals on which the *double buffering* technique is used to pipeline the elaboration of samples acquired in the previous subinterval and the acquisition of new data in the current one; this avoid to lose periods of input signals in which significant disturbances may happen. Also this permits to avoid the use of an expensive synchronizing system between the input signals and

the digitizing hardware. The realized device, being based mainly on high level software, is a low-cost, programmable, extendable, user-friendly instrument which does not require further software setup for measurement data treatment as the most part of other devices commercially available. In fact, as all the virtual instruments, its behavior can be changed according to the future developments of the power quality theory and the probable consequent new AEEG's directives. Finally an in-depth analysis of the uncertainties produced by the instrument, showed that the experimental uncertainties are lower than the bounds indicated in the same standard for the Class A instruments; this means that the presented instrument could be placed in this class without problems and encourages to continue the experiments and to add improvements; so in the authors' opinion, the proposed VI would be integrated with a GSM-based data transmitter for the measurement data dispatch to some centralized data acquisition organism (like the CESI) with the aim of identification of the correlated data.

### III.B   The user interface

The image in Fig.1 shows one of the many sections of the Front Panel of the developed *VI*; to simplify the user interface and to make it more usable, the Front Panel has been organized as a collection of pages grouping various subsections of correlated controls and indicators. The first section (Fig. 1) ( the *setup section)* is devoted to the basic requirements of running the proposed instrument (setting of DAQ gain, choice of the resolution, selection of FFT analysis parameters and so on) and to the statement of both path and file name output. The second section is the page of results where the proposed quality indices are displayed. The third section is devoted to disturbances analysis and characterization (flicker, distortion, etc). For sake of brevity, the description of the other minor sections, useful to a complete characterization of power systems are here omitted.
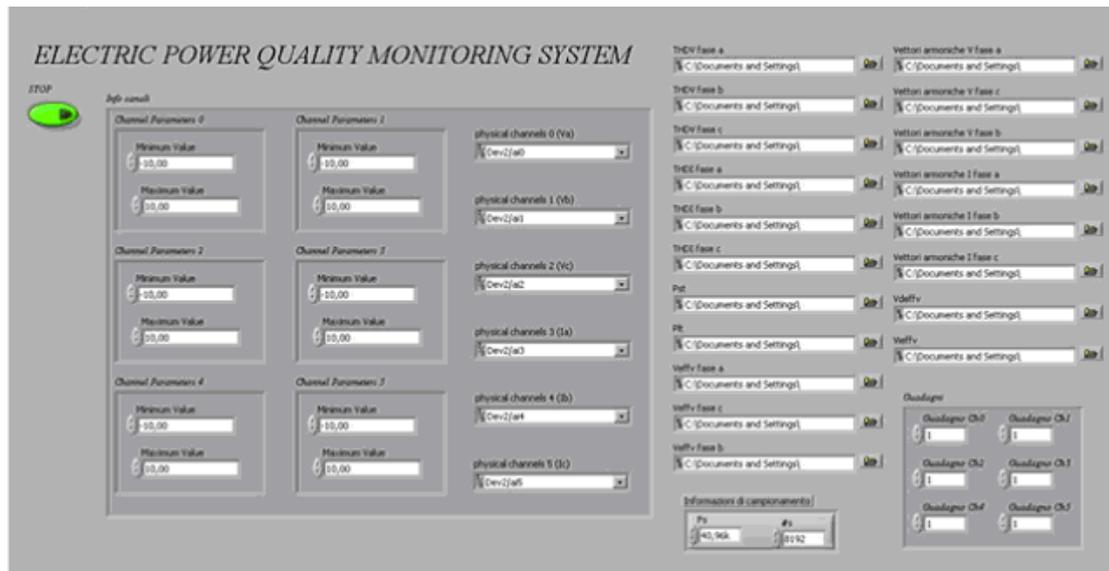


*Fig.1 – Front Panel of the developed VI: First page of the instrument*

### III.C   The spectral analysis algorithm

The VI carries out a very accurate spectral analysis with better amplitude, frequency and phases estimates in comparison with the commercial analyzer which ensures accurate measurements only for coherent sampling.

Particularly, the prototype developed in this work interpolates between the DFT (Discrete Fourier Transform) spectral rows by evaluating the *spectral shift fractional bin* $\delta_r$ as:

$$\delta_r = \left( P + \frac{1}{2} \right) \cdot \frac{\left| \bar{V}_w(L_r) \right| \cdot \left\{ \left| \bar{V}_w(L_r+1) \right| - \left| \bar{V}_w(L_r-1) \right| \right\}}{\left\{ \left| \bar{V}_w(L_r) \right| + \left| \bar{V}_w(L_r+1) \right| \right\} \cdot \left\{ \left| \bar{V}_w(L_r) \right| + \left| \bar{V}_w(L_r-1) \right| \right\}} \tag{1}$$

and obtaining the *scalloping loss* $SL(\delta_r)$:

$$\left| SL(\delta_r) \right| = \left| \frac{\delta_r \cdot \sin(\pi \delta_r)}{\pi a_1} \cdot \sum_{l=0}^{L} (-1)^l \frac{a_l}{\delta_r^2 - l^2} \right| \tag{2}$$

where $P$ is the Rife-Vincent window order, $\left|\overline{V}_w\left(L_r\right)\right|$ is the spectrum peak value and $\left|\overline{V}_w\left(L_r-1\right)\right|$ e $\left|\overline{V}_w\left(L_r+1\right)\right|$ are the spectrum samples immediately adjacent $\left|\overline{V}_w\left(L_r\right)\right|$ [9].

In the particular case of a coherent sampling $\delta_r = 0$ and $SL(\delta_r) = 1$ so that the interpolation is not necessary.

Once known the $\delta_r$ and $SL\left(\delta_r\right)$ values it is simple to estimate the amplitudes of every single harmonic of interest as:

$$A_0 = \frac{\left|X(0)\right|}{CG\cdot N\cdot\left|SL(\delta_r)\right|} \quad e \quad A_k = \frac{2\left|X(kF)\right|}{CG\cdot N\cdot\left|SL(\delta_r)\right|} \tag{3}$$

being $A_0$ and $A_k$ the DC and the $k$-th harmonic component, respectively; in the same way, both the $k$-th frequency and phase are estimated respectively as:

$$f_k = F\cdot\left(k+\delta_r\right) \quad \text{and} \quad \angle X\left(k\cdot F\right) = \arg\left[X\left(k\cdot F\right)\right] = arctg\,\frac{X_{im}\left(k\cdot F\right)}{X_{re}\left(k\cdot F\right)} \tag{4}$$

Even if the actual standardization doesn't require the voltage fluctuations amplitude measurements but only the flicker evaluation with statistic indexes like $P_{st}$ and $P_{lt}$, the proposed VI realizes the automatic envelope of the voltage fluctuations amplitude; moreover, it offers the possibility to monitor the extent of the phenomena useful for a more in-depth analysis of this problem.

## IV.    Conclusions

The potential economic consequence of an unreliable distribution network forces power distributing companies to an accurate and continuous monitoring of meaningful power quality parameters; so power monitoring system will evolve to provide still more features for distributor and user.

From this point of view, the authors present a completely digital method for the fast and accurate monitoring of the electrical power quality useful to produce real time quality/disturbance reports.

In the paper, the mathematical basis of the proposed estimation algorithm is discussed in terms of reliability and uncertainty.

Finally, the virtual instrument realized implementing this technique detects, assess and stores correctly transient disturbances occurring on the network. The first simulation shown that the results obtained using the proposed prototype do agree with the theoretical one and encourage to further develop the project in depth.

## V.    References

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