

## Low-Cost Power Quality Monitor Based on a PC

José Batista<sup>1</sup>, João L. Afonso<sup>2</sup>, Member, IEEE, and Júlio S. Martins<sup>3</sup>, Member, IEEE

<sup>1</sup>Polytechnic Institute of Bragança, Campus Sta. Apolónia, Bragança, Portugal, e-mail : jbatista@ipb.pt

<sup>2,3</sup>DEI, University of Minho, Campus Azurém, Guimarães, Portugal, e-mail: jla@dei.uminho.pt , jmartins@dei.uminho.pt

**Abstract** – This paper presents the development of a low-cost digital system useful for power quality monitoring and power management. Voltage and current measurements are made through Hall-effect sensors connected to a standard data acquisition board, and the applications were programmed in LabVIEW™, running on Windows in a regular PC. The system acquires data continuously, and stores in files the events that result from anomalies detected in the monitored power system. Several parameters related to power quality and power management can be analyzed through 6 different applications, named: “Scope and THD”, “Strip Chart”, “Wave Shape”, “Sags and Swells”, “Classical Values” and “p-q Theory”. The acquired information can be visualized in tables and/or in charts. It is also possible to generate reports in HTML format. These reports can be sent directly to a printer, embedded in other software applications, or accessed through the Internet, using a web browser. The potential of the developed system is shown, namely the advantages of virtual instrumentation, regarding to flexibility, cost and performance, in the scope of power quality monitoring and power management.

**Index Terms** – Power Quality, p-q Theory, Monitoring System, Virtual Instrumentation, LabVIEW™.

### I. INTRODUCTION

Due to the intensive use of power converters and other non-linear loads in industry and by consumers in general, it can be observed an increasing deterioration of the power systems voltage and current waveforms. The presence of harmonics in power lines results in greater power losses in the distribution system, interference problems in communication systems and, sometimes, in operation failures of electronic equipments, which are more and more sensitive since they include microelectronic control systems, which work with very low energy levels.

Because of these and other problems, the issue of the power quality delivered to the end consumers is, more than ever, an object of great concern.

International standards concerning electrical power quality (IEEE-519, IEC 61000, EN 50160, among others) impose that electrical equipments and facilities should not produce harmonic contents greater than specified values, and also specify distortion limits to the supply voltage.

But power quality problems are not restricted to harmonics. Standard IEEE 1159 classifies various electromagnetic phenomena in power systems voltage (which are related to power quality problems), namely: impulses, oscillations, sags, swells, interruptions, undervoltages, overvoltages, DC offset, harmonics, interharmonics, notches, noise, flicker, and frequency variation [1].

The economical importance of power quality can be quanti-

fied. According to EPRI (Electric Power Research Institute) power quality problems and electrical energy outages in the United States cost more than €100 billion per year. All over the world there are many companies where these problems must be minimized or eliminated in order to increase productivity [2, 3].

Power quality monitors are the best way to detect and diagnose problems in electrical power systems. However, these equipments are usually very expensive. In this paper a PC based cost-effective solution for power quality monitoring and power management will be presented.

### II. THE SYSTEM HARDWARE

The developed power quality monitor measurement system uses Hall-effect sensors: 4 voltage sensors (LEM LV 25P) and 4 current sensors (LEM LTA 50P). They can be used to measure the power system instantaneous phase to neutral voltages ( $v_{an}$ ,  $v_{bn}$  and  $v_{cn}$ ), neutral to ground voltage ( $v_{ng}$ ), phase currents ( $i_a$ ,  $i_b$  and  $i_c$ ), and neutral current ( $i_n$ ). These sensors convert the measured voltage or current values in small amplitude voltage signals. Furthermore, they isolate these signals from the power system potentials, allowing a safe operation of the developed monitoring system.

The sensors are connected to a standard data acquisition board for the PCI bus (MIO-PCI-6024E, from National Instruments). Its main characteristics are: 16 analogic channels (8 channels in differential mode), 12 bits resolution, 200 ksamples/s sampling rate, 8 I/O digital lines, a 512 samples FIFO, 2 counters/timers with 24 bits resolution, and 2 digital trigger inputs, and several acquisition modes (including DMA – Direct Memory Access). This board works with two accessories: a connections box (SCH68) and a connection cable (SH68).

A standard desktop personal computer (PC), with a 450 MHz Pentium II processor, running the Windows XP operating system, was used as the system processing unity.

### III. THE MONITORING SYSTEM SOFTWARE

The monitoring system software was developed within the LabVIEW™ (from National Instruments) graphic programming environment. A program developed in LabVIEW is designated VI (Virtual Instrument), because its appearance and functioning resemble real instruments, like scopes and multimeters. VI's use functions that manipulate the information coming from the user interface, and present it (after processing) or transfer it to files, to other programs, or even to other computers [4-6].

The system acquires data continuously, and stores in files the desired processed values, and the events that result from the detection of anomalies in the monitored power system (several parameters related to power quality are analyzed).

The acquired information can be visualized both in tables and/or through charts. It is also possible to generate reports in HTML (HyperText Markup Language) format. These reports can be sent directly to a printer, embedded in other *Windows* applications, or can be accessed through the Internet, using a web browser.

Furthermore, after the acquisition, processing and analyses of the information, data and warnings can be sent through Internet or wireless technology. Fig. 1 shows a block diagram of the developed power quality monitoring system.

After definition of the general characteristics and specifications of the monitoring system, a top-down and modular methodology for the development of the system software was followed. Six applications were developed: “Scope and THD”, “Strip-Chart”, “Wave Shape”, “Sags and Swells”, “Classical Values”, and “p-q Theory”.

These applications consist of different software modules. Inside each module there is a first hierarchical level, which contains the main VI.

Descending in the hierarchy, inside each sub-level, other operations can be accessed and manipulated by the user through menus and submenus.

Fig. 2 illustrates a basic *LabVIEW* structure used to implement continuous acquisition. It is constituted by 2 *While* cycles. The first one initializes and introduces the necessary system parameters. The second implements data reading operations from the circular buffer.

The VI “AI CONFIG” configures the acquisition board to work with analog inputs, and allocates a memory buffer for continuous acquisition. The VI “AI START” initiates the continuous acquisition. The VI “AI READ” reads a certain number of samples from the circular buffer (it is inside a *While* cycle, which ends only when the program is terminated). The VI “AI CLEAR” releases all resources associated to the running task, including the buffer. The VI “General ERROR Handler” is used to monitor *LabVIEW* errors, and presents a code and a message if an error is detected.

In the programming structure various *Sub-VIs* can be included to perform the desired processing, like, for instance, calculation of RMS (Root Mean Square) and mean values, harmonics analysis and THD (Total Harmonic Distortion) calculation, and so on.

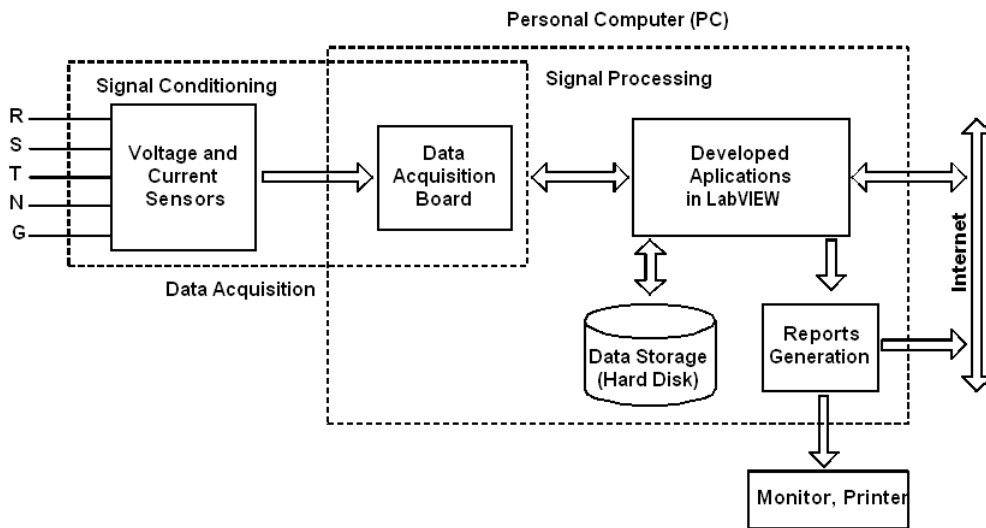


Fig. 1 Power quality monitoring system block diagram

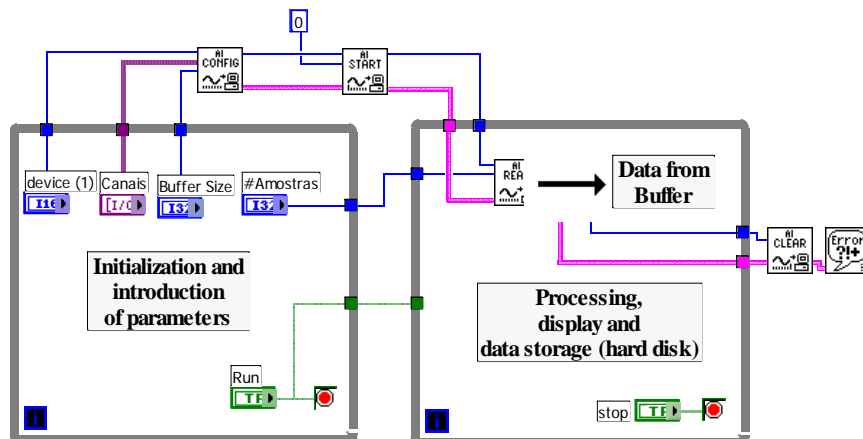


Fig. 2 Example of a basic *LabVIEW* structure

#### IV. THE DEVELOPED APPLICATIONS

The developed system allows the measurement, monitoring and analysis of different parameters of the observed electric system, by selecting the desired application.

All 6 developed applications for the power quality monitor provide data storage and report generation.

Next, each one of the developed applications is described.

##### A. Application “Scope and THD”

This application is a typical example of virtual instrumentation, because it “imitates” a digital scope with 8 isolated channels (4 voltage channels and 4 current channels) with the usual main basic functions: time base, vertical gain, trigger setup (slope, level and source), and readouts, like signal frequency, “True RMS” values, mean values, peak-to-peak values, etc. It is important to highlight that this application calculates the “True RMS” value, since many instruments in fact calculate a false RMS value, based on the calculation of the mean value of the “rectified” waveform (supposed to be sinusoidal), and on the crest factor value (the reason between RMS and mean values). It is also possible to calculate the harmonics and THD of any of channel.

With this application it is possible to visualize up to 8 signals simultaneously, with a sampling rate of 25 kHz per channel. If only one channel has to be observed it can be done with a sampling rate of 200 kHz. With 2 channels the sampling rate would be 100 kHz, and so on.

The application can also generate reports in HTML format, and register data in files, which can be manipulated by other standard software tools that run on Windows, like Excel or Matlab. New functionalities can be easily added to the application, taking advantage of graphic programming and the use of the *SubVI*'s potential.

Fig. 3 shows the window that appears on the PC screen with an example of the application “Scope and THD”. In this example only 2 channels are active: the voltage and the current of a single-phase non-linear load. The waveforms are shown in the left side of the window and the harmonics of the current are shown in the right side.

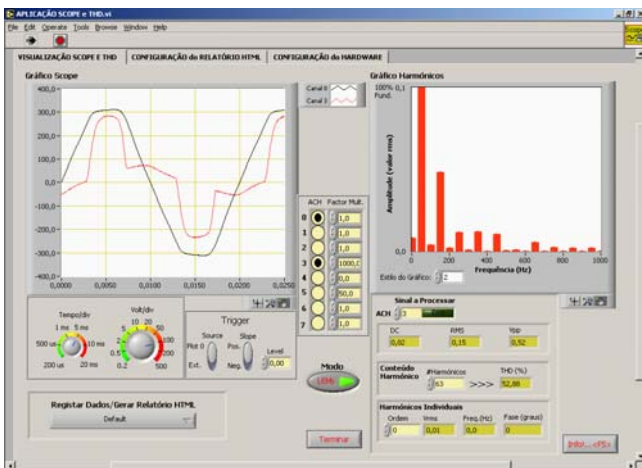


Fig. 3 The window for the Application “Scope and THD”

##### B. Application “Strip Chart”

This application allows the calculation, registration and monitoring of “True RMS” values along the time. It can register the “True RMS” values of 4 voltages (the 3 phase to neutral voltages and the neutral to ground voltage) and 5 currents (the 3 phase currents, the neutral current and the ground current). The ground current is not measured, but calculated from the 3 phase currents and the neutral current. The user can set the strip chart time interval from 1 minute to 9 days. The signals can be visualized on-line if it is desired, and the application can be interrupted at any time (in any case the data is always stored in the PC hard disk). It is possible to see the registered data at any time, and HTML reports can be produced. The time interval of the registered data can be adjusted by the user, avoiding unnecessary data storage.

Fig. 4 presents the window for the application “Strip Chart” when data is showed on-line on the PC screen. The left side of the window shows voltage strip-charts and the right side shows current strip-charts.

##### C. Application “Wave Shape”

This application detects distortions in the voltage waveforms of the 3 phases and registers these anomalies in file. In continuous acquisition, the sampled values of the power system cycle  $n$  are compared with the sample values of cycle  $n-1$ . If the result of the comparison exceeds a previously established limit (given by pre-specified tolerance values), the occurrence of an anomaly is considered, and the event is registered in file. There are always two cycles of the voltage signals being processed, and when a disturbance is detected, the samples of these two cycles, the samples of two cycles before them, and of two cycles after them, are all registered. Therefore, 6 cycles are registered when an anomaly is detected. The registry is made for the 3 phase voltages, even if the anomaly is detected in only one of the phases.

The critical aspect in the implementation and execution of this application relies on the fact that it must operate continuously without losing samples. The tests performed assured the correct operation of this application.

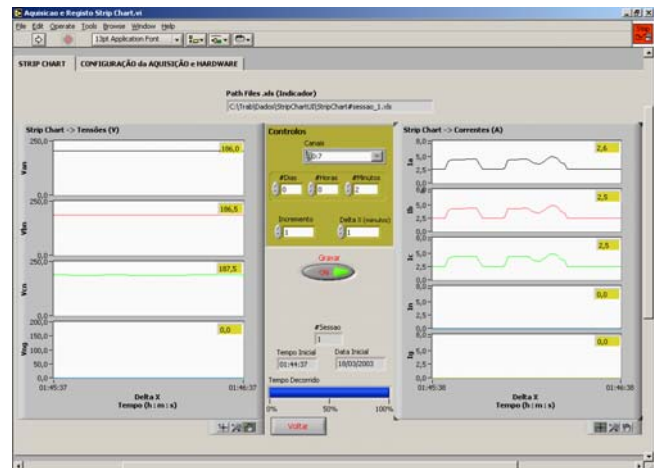


Fig. 4 The window with the Application “Strip Chart” running

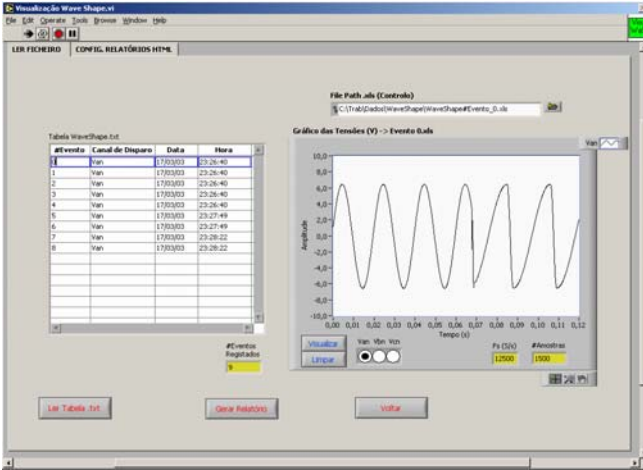


Fig. 5 Window with recorded data from the Application “Wave Shape”

Fig. 5 presents a window of the application “Wave Shape” that appears on the PC screen. The table in the left side shows all the registered events with the following information: event number, channel in which the anomaly was detected, date and instant of occurrence. The waveform presented in the right side of the window shows 6 cycles of the channel 1 waveform ( $v_{an}$ ), but the other phase to neutral voltages ( $v_{bn}$  and  $v_{cn}$ ) can also be shown by selecting them.

#### D. Application “Sags and Swells”

This application detects, and registers in a file, short-time and long-time sag and swell events detected in the monitored voltages. The application simultaneously compares the measured values with the rated values of the phase to neutral voltages and neutral to ground voltage. The operating tolerances are introduced by the user, which can apply different standards in relation to the accepted behavior of the measured voltages. The user can also make an option for operation with analysis at each cycle or at each half cycle.

Fig. 6 shows a window of this application, which includes a table that presents all registered sags and swells with the following information: date, hour, phase voltage where the problem was detected, minimum or maximum “True RMS” value of the sag or swell, duration of the event, type of event (sag or swell).

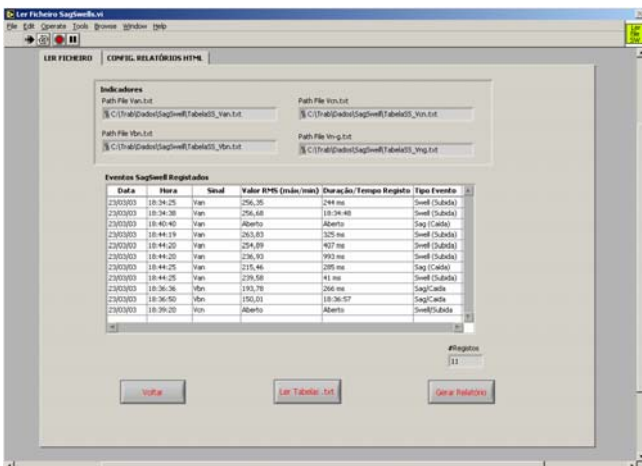


Fig. 6 Window with data from the Application “Sags and Swells”

#### E. Application “Classical Values”

This application calculates the “True RMS” amplitude values and phase angles of each voltage and current, and also calculates the impedance amplitude and angle (per phase). In addition to the numerical values, the same information can also be plotted on-line. Voltage and current unbalance, and total and displacement power factors are also calculated. The values of kWh (energy) and kVarh (reactive “energy”) are also registered.

The application allows operation in two modes: “Acquisition” and “Simulation”. In the “Simulation” mode all the calculations are made based on signals generated within LabVIEW. These signals parameters (amplitude, angle and frequency) are configured by the user, and it is possible to synthesize a signal with a fundamental frequency and its harmonics. In the “Acquisition” mode the calculations are made with real signals, acquired by the voltage and current sensors.

Fig. 7 presents an example window of the application “Classical Values” in which are showed, on-line, the vectors of the phase to neutral voltages, phase currents and phase impedances, all for the fundamental frequency (50 Hz, in this case).

#### F. Application “p-q Theory”

This application calculates and presents the values produced by the p-q Theory. This theory, also known as “Instantaneous Power Theory” was proposed in 1983 by Akagi *et al.* to control active filters [7, 8]. It is based on instantaneous voltage and current values in three-phase power systems with or without neutral wire, and is valid both for steady-state or transient operation, as well as for generic voltage and current waveforms. The p-q theory consists basically in an algebraic transformation (Clarke transformation) of the three-phase voltages and currents in  $a-b-c$  coordinates into  $\alpha-\beta-0$  coordinates, followed by the calculation of the p-q theory instantaneous power components.

The knowledge of these components can be useful to analyze a three-phase power system, since they allow viewing some of the power quality problems under a different point of view [9, 10].

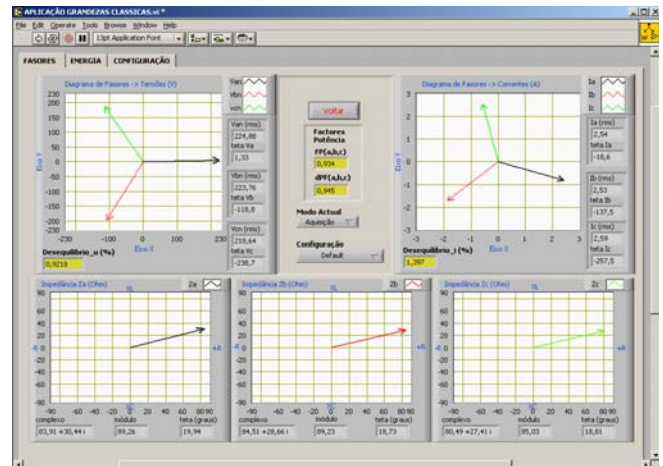


Fig. 7 Window with the Application “Classical Values” running

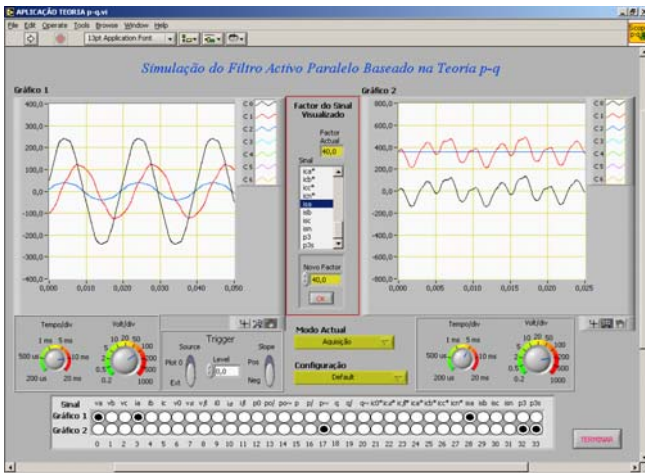


Fig. 8 Window of the Application “p-q Theory”

This application can also calculate the values of currents and instantaneous power that the source would have to supply if a shunt active power filter was used to compensate for harmonics, reactive power and zero sequence current. The software computes all the quantities which are important to the control of the active filter, and allows the visualization of all relevant signals: voltages, currents and power components, at load, source and active filter. The signals can be shown in  $a-b-c$  or  $\alpha-\beta-0$  coordinates and presented through a window showed in Fig. 8.

The application allows three different modes of operation: “Acquisition”, “Simulation *LabVIEW*” and “Simulation *Matlab/Simulink*”. In the “Acquisition” mode all p-q Theory calculations are made from real voltage and current signals, obtained with the sensors and acquisition board. The “Simulation *LabVIEW*” mode has all functionalities of the previous mode, but uses signals produced with *LabVIEW VI*'s. Harmonic components can be added to any simulated voltages or currents. In the “Simulation *Matlab/Simulink*” mode the simulation and visualization of the signals is performed in the *Matlab* environment. It is done without closing the current application, which runs on *LabVIEW*. The *Matlab* simulation is executed through a *mdl* file developed in *Simulink*. The menus for this graphical user interface were developed with the *Matlab GUIDE* (Graphical User Interface Development Environment) tool.

## V. COMPARISON WITH COMMERCIAL SYSTEMS

After researching the power quality monitors and power management systems commercially available in the market, it could be concluded that, the main manufacturers present highly developed products, which basically present the following aspects:

- The characteristics and performances of the equipments are usually very good in the top line products.
- The software packages developed specifically by each manufacturer, sometimes exploring Internet technology, enriches the management of energy and monitoring of power quality, allowing the development of distributed applications.
- These high end commercial products are usually very ex-

pensive.

Some manufacturers present a base module with several optional modules (the optional modules only work with the base module). The software and accessories must also be purchased. As an example, a base module capable of performing harmonics analysis, RMS values calculations and sags and swells detection can cost about €6000. An optional module for transitory detection can range from €2000 to €5000. An optional module for monitoring and management of energy can cost €2000. The system software (strictly necessary) can cost about €1000, and the software to allow report generation can cost another €1000. Therefore, a complete system can cost as much as €15000, or even more, and the accessories (voltage probes, current probes, etc) must also be purchased.

The commercial systems usually demand specific software and additional modules to allow Internet applications, which can imply in high costs.

It is important to highlight that the costs of the power quality and power management commercial tools depend on their characteristics and performances, and also on the manufacturers. There are also products ranging from prices as low as €700 to €3000, but they can be very limited, and it is usually necessary to use a PC to download the recorded data from these equipments, in order to perform processing and report generation.

The power quality monitor proposed in this paper has the following characteristics:

- Great flexibility and additional functions regarding the commercial products (the Application “p-q Theory”, for instance). Acquisition and visualization of up to 8 independent channels, simultaneously. The acquisition sampling rate is limited only by the acquisition board, which permits 25 ksamples/s per channel if all channels are used simultaneously, or 200 ksamples/s if only one channel is used. The user can set the sampling data registry.
- Large data storage capacity. Since data is stored in hard disk, the proposed solution surpasses the majority of commercial products regarding storing capacity.
- The proposed solution presents a friendly interface with the user. Since it works in a PC with a *Windows* operating system, the user can handle the developed applications with the help of the keyboard, mouse and a large colored monitor, and the interfaces are windows with the advantages of the point-and-click procedures.
- It generates HTML reports that can be accessed through Internet, without any additional software. It can also generate data to other *Windows* applications, like *Excel* or *Word*. The proposed power quality monitoring system can be considered a low-cost solution, since, besides the PC, it just uses 4 voltage and 4 current Hall-effect sensors, with a total cost of about €200, and a standard acquisition board and its accessories, which have a total cost of nearly €1100 (there are other less expensive acquisition boards, from other manufacturers, that could be used). The prices of PCs available in the market are always decreasing, and since it is not necessary to use a top model for the monitoring system, a dispensable PC can be used, with minimum additional

costs. The results presented in this paper were obtained using a PC with a 450 MHz Pentium II processor, 256 MB of RAM Memory, running *Windows XP*.

## VI. CONCLUSIONS

Nowadays there are several types of commercial tools in the market that can be used to monitor power quality problems or to perform power management studies. However, when these equipments present good characteristics and performances they are usually very expensive.

This paper describes a developed system that can be very useful for power management and power quality monitoring, suitable for industrial or commercial facilities, or even for research purposes, which uses a reduced cost platform. To accomplish that, Hall-effect voltage and current sensors, a generic data acquisition board, a regular PC, and a graphical programming language (*LabVIEW*<sup>TM</sup>), running on *Windows*, was used.

The developed monitoring system is flexible, presents a user-friendly interface and a large data storage capacity, since it uses the PC hard disk for that purpose. It generates HTML reports that can be accessed through Internet, and can also generate data for other applications running in the *Windows* environment.

One of the developed applications calculates the values of the p-q Theory for a three-phase power system. This type of analysis was included because it can help diagnosing problems related to electrical power quality. This application can also estimate the new values of instantaneous currents and power delivered by the power source, if a shunt active power filter was used to compensate for harmonics, reactive power and unbalanced loads in the analyzed power system.

This application allows on-line operation (with data obtained in real-time), operation with previously recorded data, and operation from simulated data, produced by *LabVIEW* or *Matlab/Simulink*.

## VII. ACKNOWLEDGEMENT

The authors are grateful to FCT (Fundação para a Ciência e a Tecnologia), project funding POCTI/ESE/41170/2001.

## VIII. REFERENCES

- [1] R. C. Dugan, M. F. MacGranaghan, H. W. Beaty, *Electrical Power Systems Quality*, MacGraw-Hill, 1996.
- [2] R. Redl, P. Tenti and J. Van Wyk, "Power Electronics Polluting Effects", *IEEE Spectrum*, May 1997, pp. 33-39.
- [3] R. Ross, T. Assis, L. Brasil, "Investigação da Qualidade de Energia Eléctrica em Clientes Industrias da RGE", *IV SBQEE*, Porto Alegre, Brazil, 2001.
- [4] J. Travis, *Internet Applications in LabVIEW*, Prentice Hall, 2000.
- [5] G. W. Johnson, *LabVIEW Power Programming*, McGraw-Hill, 1998.
- [6] R. Bitter, T. Mohiuddin, M. Nawrocki, *LabVIEW Advanced Programming Techniques*, CRC Press LLC, 2001.
- [7] H. Akagi, Y. Kanazawa, A. Nabae, "Generalized Theory of the Instantaneous Reactive Power in Three-Phase Circuits", *IPEC'83 - Int. Power Electronics Conf.*, Tokyo, Japan, 1983, pp. 1375-1386.
- [8] H. Akagi, Y. Kanazawa, A. Nabae, "Instantaneous Reactive Power Compensator Comprising Switching Devices without Energy Storage Components", *IEEE Trans. Industry Applic.*, vol. 20, May/June 1984.
- [9] E. H. Watanabe, R. M. Stephan, M. Aredes, "New Concepts of Instantaneous Active and Reactive Power in Electrical Systems With Generic Loads", *IEEE Transactions on Power Delivery*, Vol. 8, n°. 2, April 1993.
- [10] J. Afonso, C. Couto and J. Martins, "Active Filters with Control Based on the p-q Theory", *IEEE Industrial Electronics Society Newsletter*, vol. 47, n° 3, Sept. 2000, pp. 5-10.