

PROPOSAL OF A CROSS-PLATFORM VIRTUAL POWER ANALYZER BASED ON IEEE STANDARD 1459-2010

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Abstract: This paper proposes the implementation of a virtual energy analyzer using open source software. The analyzer uses the power definitions presented in the IEEE Standard 1459-2010. This standard defines the power measurement under sinusoidal, nonsinusoidal, balanced, and unbalanced conditions. The virtual analyzer uses the QT framework that provides easy cross platform compilation. Therefore, the software can be easily ported to different platforms such as Windows, Linux and Mac OS. *Copyright © 2011 CBEE/ABEE*

Keywords: Virtual instrumentation, signal processing, power quality.

1 INTRODUCTION

The electrical energy distribution systems are undergoing important changes, not only in the supply, but also in information concerning tariffs and energy quality (GHERASIM et al, 2004).

The increasing demand for electronic equipments has been the most important cause of power quality deterioration (MOREIRA et al, 2005). The single-phase loads fed by three-phase systems can result in phase current imbalance. Hence, some neutral current may appear. These neutral currents, when high, can overload transformers, voltage distortion and common mode noise (GRUZS, 1990).

Therefore, the voltage and current monitoring can help to set strategies to compensate these distortions, and make efficient tariff methods (GRUZS, 1990).

Conventional instrumentation to energy quality measurement usually requires high investments, and this provides a search of alternatives and more economical ways for this purpose. In (MOREIRA et al, 2005), a virtual instrumentation is proposed for power monitoring. However, the analyzer is developed under a proprietary and expensive software and is based on the trial-use IEEE 1459-2000. Besides, it relies under a proprietary acquisition board that increases the cost of the overall instrumentation.

As an alternative, this paper proposes the use of open source software to develop the virtual power analyzer. In addition, the signal acquisition is made by

common digital controllers found in industry. Moreover, the software can be easily recompiled to different platforms. Hence, a low cost virtual instrument, that provides the necessary information about power quality using the IEEE standard 1459-2010, is achieved.

The paper is organized as follows: Section 2 summarizes the IEEE Std 1459-2010; Section 3 describes the proposed solution to achieve a low cost virtual instrument; Section 4 introduces the proposed software implementation; Section 5 presents some simulation results to show the viability of the proposal; Section 6 concludes the paper.

2 OVERVIEW OF THE IEEE STANDARD 1459-2010

The IEEE Standard 1459-2010 (IEEE, 2010) defines power measurement under sinusoidal, nonsinusoidal, balance or unbalanced conditions. Its first publication, in trial-use, was in January 2000. After this publication, several discussions about their definitions appeared (HUGHES, 2002; SEGUI-CHILET et al, 2007; MORSI e EL-HAWARY, 2008; ORTS-GRAU et al, 2011). In March 2010, a review was introduced, with some important changes and corrections.

The definitions introduced in the aforementioned standard were developed to guide what values must be measured or monitored for revenue purposes, engineering economic decisions, and determination of major harmonic polluters.

The definitions include the apparent, active and reactive powers computation, defining what is generated, transmitted, distributed, and sold by the electric utilities and bought by the end users.

2.1 Active Power

The active power is the average value of the instantaneous power during the measurement time interval τ to $\tau+kT$, defined by

$$P = \frac{1}{kT} \int_{\tau}^{\tau+kT} p(t) dt, \quad (1)$$

where $T=1/f$ is the cycle period, k is a positive integer number that represents the number of analyzed cycles, τ is the moment when the measurement starts and $p(t)=v(t)i(t)$ is the instantaneous power.

The active power can be divided into fundamental, P_1 , and harmonic, P_H , given by

$$P_1 = \frac{1}{kT} \int_{\tau}^{\tau+kT} v_1(t) i_1(t) dt, \quad (2)$$

$$P_H = P - P_1. \quad (3)$$

In a three-phase system, the active power can be defined by the sum of phases active powers

$$P = P_a + P_b + P_c. \quad (4)$$

2.2 Reactive Power

The reactive power is produced when there are inductive, capacitive, or nonlinear elements connected to the system. It does not represent the used power that might be extracted from the system, but can cause increased losses and excessive voltage peaks (IEEE, 2000).

The reactive power Q is given by

$$Q = \frac{\omega}{kT} \int_{\tau}^{\tau+kT} i(t) \left[\int_{\tau}^{\tau+kT} v(t) dt \right] dt, \quad (5)$$

where $\omega=2\pi f$ is the angular frequency.

The same way as the active power, the reactive power also can be decomposed in its fundamental Q_1 and harmonic Q_H components

$$Q_1 = \frac{\omega}{kT} \int_{\tau}^{\tau+kT} i_1(t) \left[\int_{\tau}^{\tau+kT} v_1(t) dt \right] dt, \quad (6)$$

$$Q_H = Q - Q_1. \quad (7)$$

In a three-phase system, the total reactive power is given by

$$Q = Q_a + Q_b + Q_c. \quad (8)$$

2.3 Apparent Power

For a single-phase load, the apparent power S can be interpreted as the maximum active power that can be transmitted through the same line keeping the load rms voltage and current constant. It is given by the product of the rms voltage and the rms current

$$S = VI. \quad (9)$$

For a three-phase system, the IEEE Standard 1459-2010 defines the effective apparent power as

$$S_e = 3V_e I_e, \quad (10)$$

where V_e and I_e are the effective rms voltage and current, respectively, given by

$$V_e = \sqrt{\frac{3(V_a^2 + V_b^2 + V_c^2) + V_{ab}^2 + V_{bc}^2 + V_{ca}^2}{18}} \quad (11)$$

and

$$I_e = \sqrt{\frac{I_a^2 + I_b^2 + I_c^2 + I_n^2}{3}}. \quad (12)$$

These quantities are defined for a four-wire system. For a three-wire system these values become

$$V_e = \sqrt{\frac{V_{ab}^2 + V_{bc}^2 + V_{ca}^2}{9}}, \quad (13)$$

$$I_e = \sqrt{\frac{I_a^2 + I_b^2 + I_c^2}{3}}. \quad (14)$$

For a balanced and sinusoidal system, the effective apparent power S_e is equal to the conventional apparent power $S = 3V_{ln} I = \sqrt{3} V_{ll} I$, where V_{ln} e V_{ll} are the line-to-neutral and line-to-line rms voltages, respectively. For sinusoidal unbalanced or for nonsinusoidal balanced or unbalanced situations, S_e allow rational and correct computation of the power factor.

The effective apparent power can be decomposed in its fundamental (S_{e1}), harmonic (S_{eH}) and nonfundamental (S_{eN}) components. The nonfundamental apparent power (S_{eN}) quantifies the overall amount of harmonic pollution delivered or absorbed by a load. It is defined by harmonic apparent power (S_{eH}), the segment of nonfundamental nonactive power due to current distortion (D_{eI}) and the segment of nonfundamental nonactive power due to voltage distortion D_{eV} . These components are given by the follow equations.

$$S_{e1} = 3V_{e1} I_{e1}, \quad (15)$$

$$S_{eH} = 3V_{eH} I_{eH}, \quad (16)$$

$$S_{eN}^2 = S_e^2 - S_{e1}^2 = D_{e1}^2 + D_{eV}^2 + S_{eH}^2, \quad (17)$$

$$D_{e1} = 3V_{e1}I_{eH}, \quad (18)$$

$$D_{eV} = 3V_{eH}I_{e1}. \quad (19)$$

2.4 Nonactive Power

In addition to the active reactive and apparent powers, there is the definition of nonactive power. It lumps together both fundamental and nonfundamental nonactive components, that in the past was called “fictitious power”. It is given by

$$N = \sqrt{S^2 - P^2}. \quad (20)$$

The nonactive power shall not confused with the reactive power, because only when the waveforms are perfectly sinusoidal we have $N = Q_1 = Q$.

3 PREREQUISITS OF THE PROPOSED SOLUTION

This section describes the prerequisites of the proposed solution. The main goal is to develop a power quality monitoring and analysis system, with focus in using free software to implement the IEEE Standard 1459-2010 definitions.

One of the advantages to use computer based software, as opposed to an acquisition system embedded software, is the shorter development time. Another important factor is the easyness to update or to implement new signal processing methods to compy to new standards. As the developed software is not embedded in the acquisition system, it is possible to combine different information of different sensors and acquisition systems, to validate the obtained data.

Another determinant aspect to choose the development for personal computers is its large potential processing power and memory storage capacity. Nowadays, the multicore processors are widespread. It enable the possibility to exploit this feature and make several computations in parallel, reducing the processing time for obtaining results.

The fact that the implemented software is developed using free and open source frameworks and tools reduces its cost of developing. It makes this proposal an attractive alternative to proprietary and expensive equipments already available.

Other project requisite is that the software must be cross-platform. That is, it must run under Windows, Linux or Mac OS operating systems. It allows the user to choose an operating system already available in his computer to run the software, or change it to a lower cost PC system.

The system’s operation sequence is represented by the flowchart in Figure 1. In the first step we have the conditioning of the signal. The resulting data is passed

to a digital signal controller (DSC-TITMS320F28335). The DSC is responsible by the A/D conversion of the grid voltages and currents, and the sample rate can be configured in software. In this work the sampling rate is 15360 samples/s. After the A/D conversion, the DSC prepare the data to send to the USB module. The USB module is responsible for the connection with the PC. This connection is used to send the acquired data (voltages and currents) to the processing software in the PC. The computer reads these data and extracts the information of interest. The PC is also responsible for the presentation of the results.

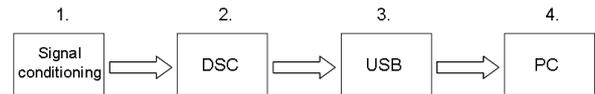


Figure 1: System’s operation sequence.

Modules 1-3 can be choose to optimize the cost/benefit for each case. The third module has direct contact with the computer. Only a change in this module may require some software adjustment. This modular structure allows system’s parts to be used separately for other projects.

Module 1 was designed to be used with single-phase and three-phase systems. Its flowchart is shown in Figure 2.

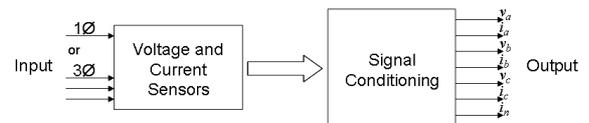


Figure 2: Acquisition module flowchart.

In this paper is was used Hall effect sensors to measure currents and voltages and it is also responsible to provide electric isolation. Signal conditioning circuits are responsible to adjust the levels of the analog signal to perform the digital conversion, adjusting the voltages within ADC acceptable limits. This circuit also introduces anti-aliasing filters and electronic protection for the ADC.

4 THE SOFTWARE

The software is divided in four modules: (1) acquisition and data logger; (2) IEEE Standard 1459-2010; (3) energy analyzer system; and (4) graphical user interface. Its structure is represented by Figure 3.

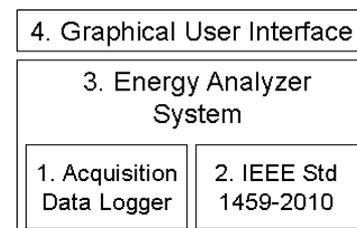


Figure 3: Developed software structure, shown the four modules and their connections.

Module (1) is responsible by data reading. The data can be obtained by a text file or the USB interface,

when the data come from the acquisition system. Its data logger feature allows to record the data in a file or data base, also enabling the reading of these data. This module can be expanded to enable reading and writing to other sources, like network, web services, and others.

Module (2) applies the computations defined by IEEE Standard 1459-2010. It receive the data read by the first module and, after the necessary computations, provides the values of powers and energy quality indexes, as described by the standard. The link between these modules is made by the third module, the energy quality module (3).

An important point is that the module (1) and (2) are independent, and they don't need other modules or components for their operation. Thus, both can be used in other projects that may need such features.

Finally, the last module (4) refers to the software's graphical user interface, and defines how the data will be presented to user. The interface can be changed, enabling the software to run in other devices and platforms, like mobile devices. This can be done without additional changes in the other three modules.

This modularity allows parts of software be used in other projects, and also new functionalities to be implemented in these modules to meet the needs of this or other projects, minimally affecting the operation of the software.

This expansion opens up almost limitless horizons for its use, both the software and the system as a whole.

4.1 Programming Language and Tools

For the software development it was chosen the C++ programming language. C++ provides the use of the object orientation paradigm, cross-platform feature, it is compiled directly to native code and has available many free tools for development and builds.

C++ language was initially designed to manage large-scale applications, but their resources can be applied in virtually any programming task. Allied to this, the concept of object-oriented programming allows the gradual growth of the system, increases productivity and facilitates the use of similar concepts to the real world.

Among the development libraries available it was chosen Qt Framework, which provides a wide range of classes and various tools that assist in the development. It facilitates building C++ applications and enable software portability for multiple operating systems, not only for personal computers, but also for mobile devices, taking the advantage of a single source code for all platforms and the natively compilation for each system. Added to the Qt Framework, the Qwt Library is used for the charts construction.

4.2 IEEE Standard 1459-2010 Implementation

IEEE Standard 1459-2010 computations were implemented by software using discrete algorithms, and using the Kalman filter to obtain the harmonic components of the signal as presented by CARDOSO et al (2007).

To use the Kalman filter the signal to be filtered must be represented by

$$x_{k+1} = \Phi_k x_k + \Gamma_k \gamma_k, \quad (21)$$

$$y_k = F_k x_k + v_k, \quad (22)$$

$$\dim x_k = n \times 1, \quad \dim y_k = r \times 1, \quad \dim \gamma_k = p \times 1, \quad (23)$$

where γ_k and v_k are uncorrelated Gaussian white-noise sequences with means and covariances as follow

$$E\{\gamma_i\} = 0, \quad E\{\gamma_i \gamma_j^T\} = Q_i \delta_{ij}, \quad (24)$$

$$E\{v_i\} = 0, \quad E\{v_i v_j^T\} = R_i \delta_{ij}, \quad (25)$$

$$E\{\gamma_i v_j^T\} = 0, \quad E\{\gamma_i x_j^T\} = 0, \quad E\{v_i x_j^T\} = 0, \quad \forall i, j, \quad (26)$$

where $E\{\cdot\}$ denotes the expectation operator and δ_{ij} denotes the Kronecker delta function. The filtering equations is given by

$$\hat{x}_{k+1|k} = \Phi_k x_{k|k-1} + K_k (y_k - F_k \hat{x}_{k|k-1}), \quad (27)$$

where $\hat{x}_{k+1|k}$ denotes the estimate of the state vector x_{k+1} , evaluated at the time t_k . The Kalman gain K_k is

$$K_k = \Phi_k P_{k|k-1} F_k^T (F_k P_{k|k-1} F_k^T + R_k)^{-1}, \quad (28)$$

where

$$P_{k+1|k} = \Phi_k P_{k|k-1} \Phi_k^T - K_k F_k P_{k|k-1} \Phi_k^T + \Gamma_k Q_k \Gamma_k^T, \quad (29)$$

represents the covariance of the estimation error.

The signal to be filtered is represented by a signal S_k with n harmonic components, that is,

$$S_k = \sum_{i=1}^n A_{i_k} \sin(i\omega_k t_k + \theta_{i_k}), \quad (30)$$

where A_{i_k} , $i\omega_k$ and θ_{i_k} are the amplitude, angular frequency and phase of each harmonic component i at the time instant t_k , and can be modeled in state-space as follow:

$$\begin{bmatrix} x_1 \\ x_2 \\ \vdots \\ x_{2n-1} \\ x_{2n} \end{bmatrix}_{k+1} = \begin{bmatrix} M_1 & \cdots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \cdots & M_n \end{bmatrix}_k \begin{bmatrix} x_1 \\ x_2 \\ \vdots \\ x_{2n-1} \\ x_{2n} \end{bmatrix}_k + \begin{bmatrix} \gamma_1 \\ \gamma_2 \\ \vdots \\ \gamma_{2n-1} \\ \gamma_{2n} \end{bmatrix}_k, \quad (31)$$

$$y_k = \begin{bmatrix} 1 & 0 & \dots & 1 & 0 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ \vdots \\ x_{2n-1} \\ x_{2n} \end{bmatrix} + v_k, \quad (32)$$

where

$$M_i = \begin{bmatrix} \cos(i\omega_k T_s) & \sin(i\omega_k T_s) \\ -\sin(i\omega_k T_s) & \cos(i\omega_k T_s) \end{bmatrix}, \quad (33)$$

$$x_{(2i-1)_k} = A_{i_k} \sin(i\omega_k t_k + \theta_{i_k}), \quad (34)$$

and

$$x_{2i_k} = A_{i_k} \cos(i\omega_k t_k + \theta_{i_k}), \quad (35)$$

where T_s is the sample time.

Components of positive sequence are obtained by

$$v_{a_k}^+ = \frac{1}{3} v_{a_k}^f - \frac{1}{6} (v_{b_k}^f + v_{c_k}^f) + \frac{\sqrt{3}}{6} S_{90} (v_{b_k}^f - v_{c_k}^f), \quad (36)$$

$$v_{b_k}^+ = -v_{a_k}^+ - v_{c_k}^+, \quad (37)$$

$$v_{c_k}^+ = \frac{1}{3} v_{c_k}^f - \frac{1}{6} (v_{a_k}^f + v_{b_k}^f) + \frac{\sqrt{3}}{6} S_{90} (v_{a_k}^f - v_{b_k}^f), \quad (38)$$

where $S_{90} = e^{j90^\circ}$ defines the 90° phase-shift operator.

These 90° shifted values are obtained by the Kalman filter, without the use of additional filters to shift the fundamental signal (CARDOSO et al, 2007).

5 SIMULATION RESULTS

To validate the software for the single phase scenario, some waveforms were generated in Matlab, as follows:

$$\begin{aligned} v(t) &= 180 \sin(\omega t) + 30 \sin(3\omega t) \\ &+ 20 \sin(5\omega t) + 15 \sin(7\omega t) \\ &+ 9 \sin(9\omega t) \end{aligned} \quad (39)$$

$$\begin{aligned} i(t) &= 10 \sin(\omega t + \theta) + 6 \sin(3\omega t + 3\theta) \\ &+ 4 \sin(5\omega t + 5\theta) + 2 \sin(7\omega t + 7\theta) \\ &+ 1 \sin(9\omega t + 9\theta) \end{aligned} \quad (40)$$

with $\theta = \pi/6$ and $\omega = 120\pi$.

These functions were generated in order to validate the proposed system by comparing the results provided by the software with those obtained by the Matlab.

It can be noticed in equations (39) and (40) the addition of the 3rd, 5th, 7th and 9th order harmonics, both in voltage and current. There is also a phase shift in the current signal.

The voltage and current values were saved in a text file and they were read by the software. The results, as

shown in Figures 4, 5 and 6, were compared with the theoretical results. The software was implemented in a PC with Ubuntu 11.04 operational system. This comparison is shown in Table 1, where the theoretical results are in the parentheses.

Through these results, it can be seen that the developed software presents a small margin of error, within acceptable parameters. Thus, although the software is still in an early stage of development, it can be noticed their feasibility for use in practical applications.

Table 1: Comparison of results obtained by the developed software and theoretical values.

Quantity or indicator	Combined	Fundamental Powers	Nonfundamental Powers
Apparent	$S = 1155.308VA$ (1155.306 VA)	$S_1 = 900.04VA$ (900.000 VA)	$S_H = 151.213VA$ (151.279 VA)
Active	$P = 731.792 W$ (731.792W)	$P_1 = 779.454 W$ (779.423W)	$P_H = -47.661W$ (-47.631W)
Nonactive	$N = 893.99 \text{ var}$ (893.989 var)	$Q_1 = -450.03 \text{ var}$ (-450.00 var)	$D_V = 200.299$ (200.374)
Line utilization	$PF = 0.634$ (0.633)	$PF_1 = 0.867$ (0.866)	$D_I = 679.471$ (679.485)
			$D_H = 143.505$ (143.585)
			$THD_V = 0.223$ (0.223)
Harmonic pollution			$THD_I = 0.755$ (0.755)

6 CONCLUSION

This paper proposed an alternative to energy analyzers already available today. Its low cost and modularity allow its modules to be integrated to various other applications, reducing costs and time to design and develop these applications.

This modularity of hardware and software, also allows the use of the core system in projects other than those related to power analysis such as control systems and related areas.

Another important factor is the use of definitions in the IEEE Standard 1459-2010, which is the newest reference for power computations and their related values.

Besides, the proposed solution is completely cross-platform and can be easily recompiled for different operating systems. The implementation uses free software to reduce the development cost.

7 ACKNOWLEDGEMENT

The authors would like to thank to FINEP, CAPES, SETI, CNPq and Fundação Araucária for the financial support.

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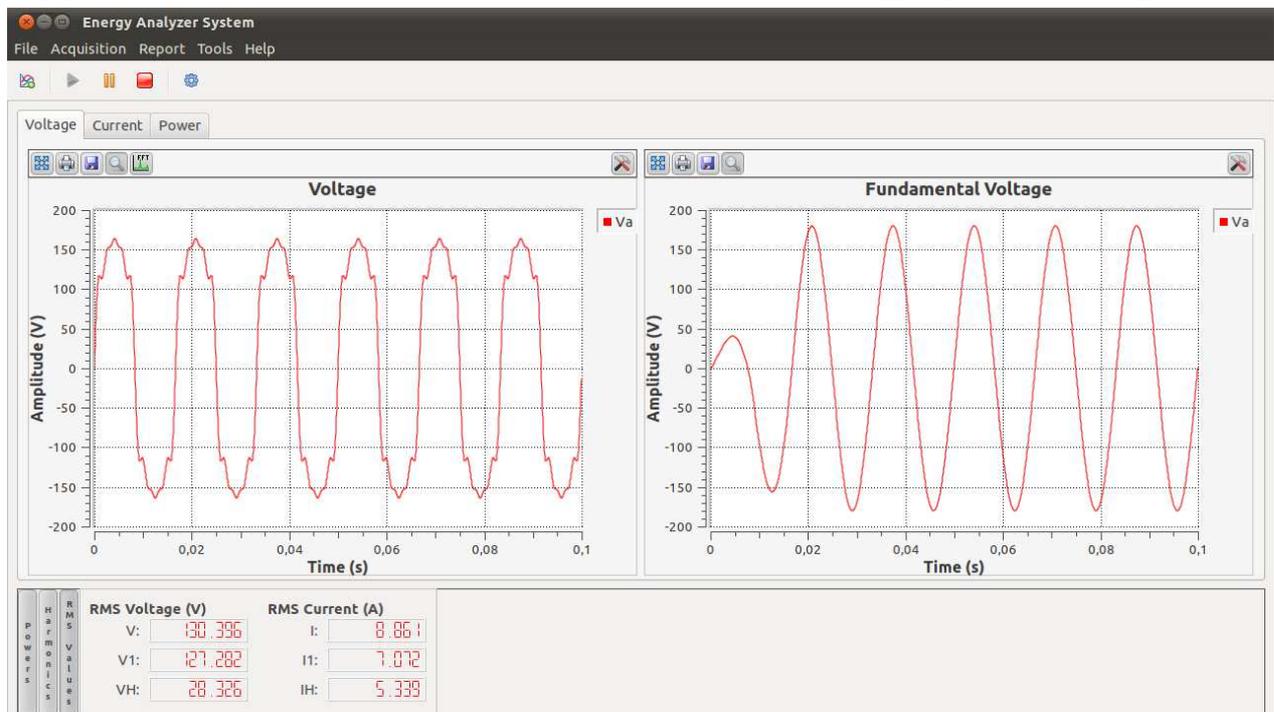


Figure 4: Developed software preview showing acquired and filtered voltage signals, and calculated rms voltages and currents.

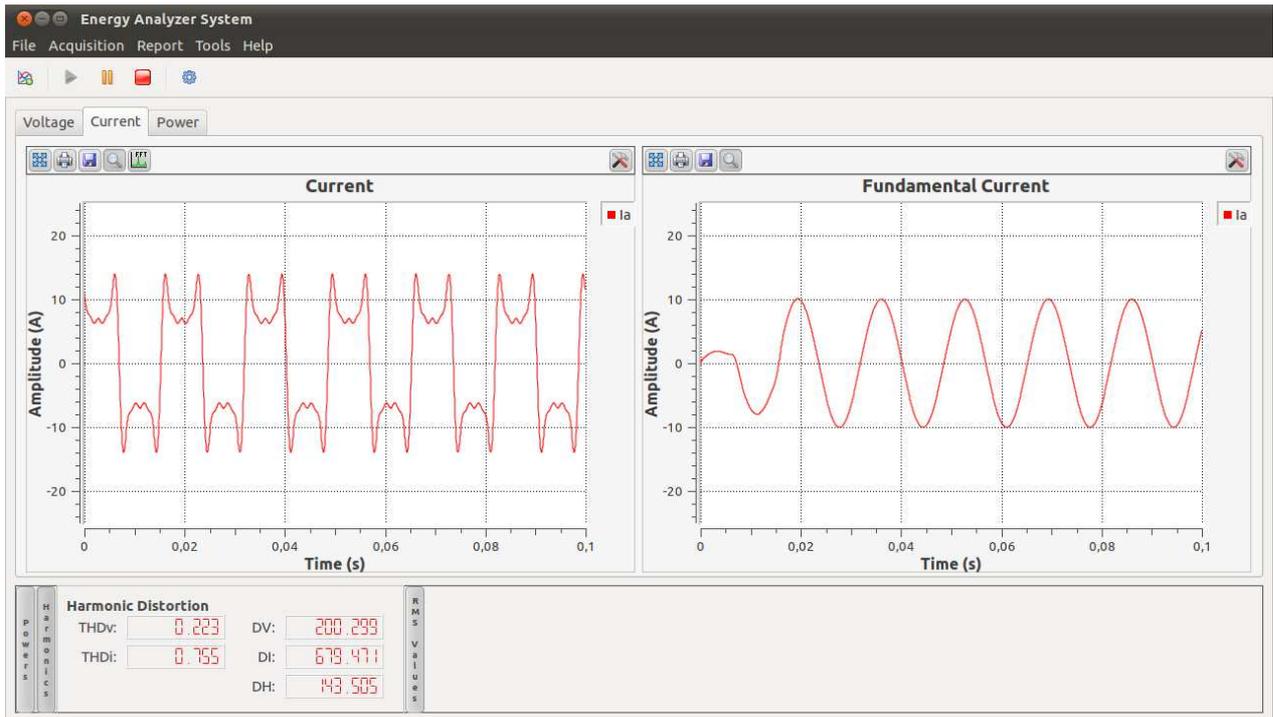


Figure 5: Developed software preview showing acquired and filtered current signals, and calculated harmonic distortion values.

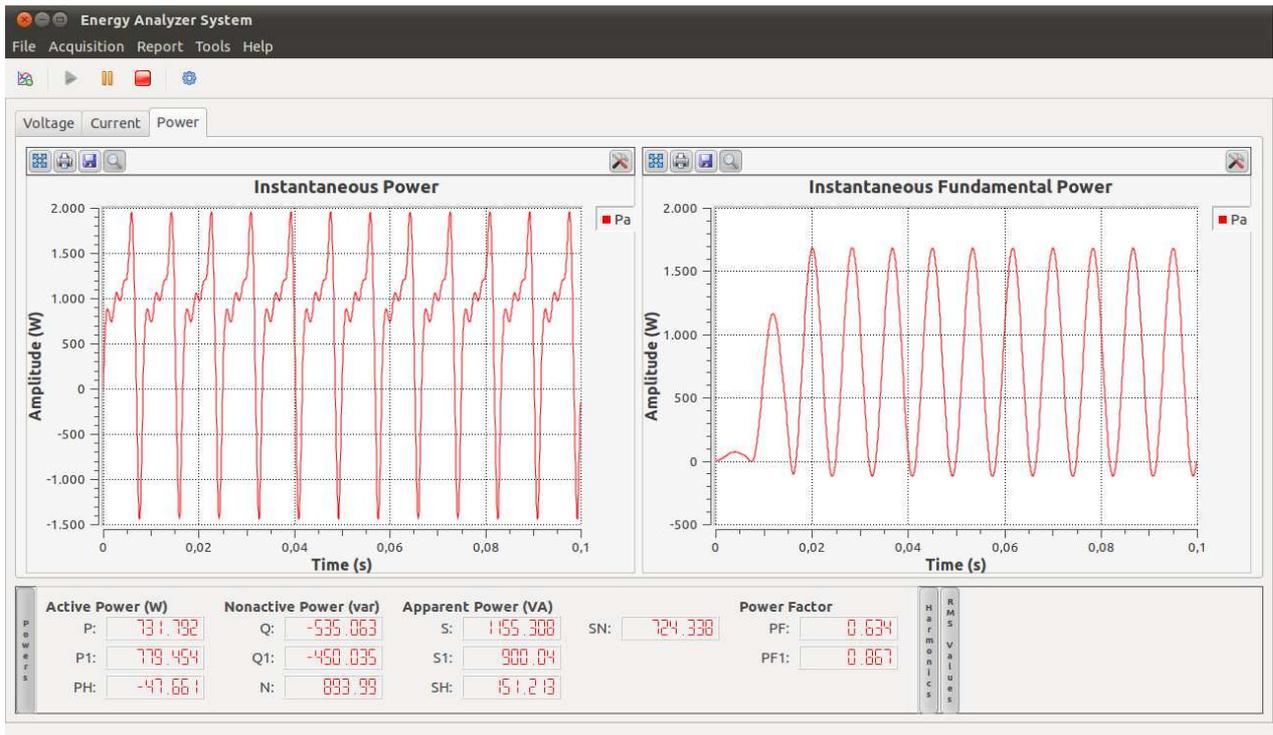


Figure 6: Developed software preview showing instantaneous power signals, and calculated power values.