zEnergy: An Open Source Project for Power Quality Assessment and Monitoring

F.G. Montoya and A. Alcayde and P. Sánchez
Area de Ingeniería Eléctrica
Escuela Politécnica Superior
Universidad de Almería
04120 Almería (Spain)
Email: pagilm@ual.es, aalcayde@ual.es

J. Gómez
Dpto. de Lenguajes y Computación
Escuela Politécnica Superior
Universidad de Almería
04120 Almería (Spain)
Email: jgomez@ual.es

F. Martín
Dpto. de Ingeniería Eléctrica.
Universidad de Málaga.
29013 Málaga (Spain)
Email: fimartin@uma.es

Abstract—**In this paper, a new open source project focused on power quality assessment and monitoring for low voltage power systems is presented. Power quality (PQ) is a crucial matter for proper and reliable operation of industrial or home electrical appliances. In order to improve PQ techniques, efforts are made to develop smart sensors that can report near real-time data. Proprietary software and hardware on dedicated computers or servers processes these data and shows relevant information through tables or graphics. In this situation, interoperability, compatibility and scalability are not possible because of the lack of open protocols. In our work, we introduce zEnergy, an open source platform for computing, storing and managing all of the information generated from smart sensors. We apply the most up-to-date algorithms developed for power quality, event detection, and harmonic analysis or power metering. zEnergy makes use of cutting-edge web technologies such as HTML5, CSS3 and Javascript to provide user-friendly interaction and powerful capabilities for the analysis, measurement and monitoring of power systems. All software used in our work is open source, running on Linux.**

I. Introduction

According to the development of our knowledge society and Internet, it is more and more notorious the wide deployment of electrical and electronic devices connected to the Grid. Not only academic or industrial but also home environments are places where those devices are becoming critical in order to deploy daily tasks: electrical appliances, computers or automated processes are examples of this kind of devices. This strong dependency forces us to maintain electrical devices in order to extend their lifespan. A key aspect in accomplishing this task is to ensure delivered voltage quality (VQ) or power quality (PQ). It has been shown [1] that poor voltage quality causes damage and early malfunction in electrical devices.

Power facilities must watch over a power quality supply in the implementation of existing regulations [2][3][4]. Sometimes ensuring good ratios of power quality can lead to problems for some facilities because of conflicting interests. On the other hand, external factors like storms, accidents, breakdowns, can affect power quality for final user supplies.

These power quality phenomena are very well known and described in literature [5][6]: sags, dips, swells, surges, outages, impulses, harmonics, transients, etc. A complete and detailed list can be found in [5]. All of these problems have been widely explained and almost solved using different techniques from the signal-processing field [7][8] [9][10][11][12][13], so there is a lot of well-known algorithms that allow us to manage, identify, analyze and show large amounts of data for every transient, perturbation or event that occurs in a power network. All of these techniques, though published and readily available separately, are not usually available together in any software package for free and/or open use. Furthermore, they are neither affordable nor easy to understand for basic technical or general audiences. Today, there are several moderately powerful hardware-based commercial solutions from different companies (Fluke, Dranetz-BMI, etc), that can do the job locally. Web based solutions are being deployed to collect sensor information and send it to central servers in datacenters for processing and analysis [14][15][16][17][18], and other tools for displaying data generated by sensor equipment[19].Present and future trends indicate that interconnected sensors through WAN, PAN, LAN, 3G networks and Smartgrid projects will be the focus of more and more efforts in the scientific community.

The creation of near real-time interconnected smart sensor networks along with server processing hardware has clear advantages over traditional solutions for controlling and metering power systems. On one hand, this approach allows an exhaustive control over facilities because it is now possible to know what is happening at every moment. On the other hand, planning and maintenance are made easier thanks to the huge amount of historical and state data relating to consumption, perturbations, anomalies, etc. The previous statement implies large resource savings and also contributes to energy saving and green strategies, now in high demand by governments and green organizations.These "total control" systems allow us to effectively optimize resources and reduce costs significantly. We can therefore conclude that is a good idea to devote significant energy to developing such systems through universal and widely adopted tools.

Open source systems, being considered very secure, scalable and powerful tools, play a very important role in our society. It is well known that their use in critical and technologically advanced systems, as a core component for reliability, gives clear advantages over proprietary systems [20][21]. Putting all of this together, our goal is to present a new project

978-1-4244-9843-7/11/$26.00 ©2011 IEEE

called *zEnergy*. *zEnergy* is an integral platform for managing, analyzing, and monitoring power systems based on an open source approach for software and advanced algorithms for power quality. Specifically, we have focused on providing user-friendly interaction and powerful capabilities using cutting-edge web technologies. Its modular architecture allows adding new functionalities using customized plugins developed by third parties. This approach is preferred over a closed project because it will allow members of the Community to contribute their knowledge toward building a more reliable and secure power project.

II. System design

The aim of our system is to provide a complete and extensible platform entirely based on open source software and standard web technologies, specially focused on providing user-friendly interaction and powerful capabilities for the analysis, measurement and monitoring of electrical facilities.

A. Objectives and functionalities

Simplicity of use –allowing the user to feel comfortable and operate intuitively- is one of the main objectives in the design of any software system. The main goal of our system is to provide an easy-to-use and complete user interface based on the new standards and web technologies.

Furthermore, we believe that the system should be an open solution, making the source code available to any developer so that it can be adapted and expanded. In short, this will allow for a constant improvement of the system over the years. This also brings the advantage of the possibility of integrating free software from third parties into the system without any license restriction, reducing the development time of its components.

The open nature of the system also involves a multi-platform approach, offering freedom to implement the system in different hardware architectures by using non-restrictive programming interfaces and design standards.

Commercial monitoring systems tend to have a closed architecture with limited extensibility. That is the reason why we have focused on the development of a modular and flexible architecture so that the system can be easily expanded by providing it with an easy expansion capability allowing the creation of external plugins through several defined programming interfaces (API).

One of the most common limitations of the proprietary solutions existing in the market is the need to purchase licenses or extra hardware and software in order to monitor multiple receptors. Contrary to this, our system provides support for multiple data inputs, allowing the user to monitor any number of receptors simply by adding more sensors without any license restriction.

Legislation is another aspect to be considered. The measuring process should be done in a reliable way, following the main national and international metering standards. Nevertheless, it is possible to personalize the following elements and configuration parameters:

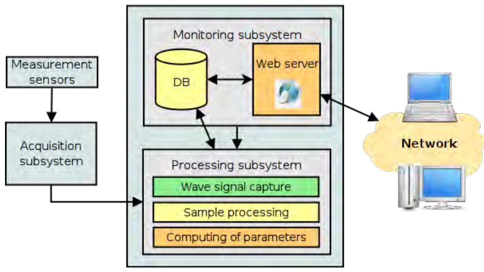

Fig. 1. Global block diagram of the system.

- Basic electrical parameters of the signals obtained from different receptors: Type of system, nominal voltage, etc.
- Data acquisition parameters: Sampling frequency, sample accuracy, processing intervals, etc.
- Event detection limits: Admissibility percentages, detection sensitivity, etc.
- Computing selection: Highest number of harmonics to obtain, tolerance to interharmonics capture, cycle RMS, frequency groups, etc.
- Data storage: Data storage time, type of database to use, etc.

Nowadays, the Fast Fourier Transform (FFT) [22] is the accepted method for signal processing. Nevertheless, despite it is being the method suggested by metering regulations, it is not the best tool for detecting some events due to certain of its characteristics [23]. In order to overcome this limitation, our system offers different analysis methods by using plugins. It can be also adapted to the metering needs of each user through individual customization of each method. Moreover, this extensible approach opens the way for the development of plugins for the latest analysis techniques of electrical signals such as wavelet analysis [24] or Kalman filters [25].

The system offers tools for querying and analyzing the historical values of monitored voltage and current signals as a main functionality. Through each of these tools it obtains information and electrical parameters of interest such as harmonics, interharmonics, RMS values and powers over time and in different aggregation intervals. With regard to billing, it is possible to obtain the expenses and the monthly forecast if the charges applied by the contracted electric company are established. In addition, it is also possible to obtain a forecast and equivalence of CO_2 emissions according to the electrical consumption produced by the system, which should be in accordance with green strategies and energy saving.

B. Architecture overview

The system is made up of three clearly distinguished subsystems [see figure 1]: Data acquisition, processing and monitoring.

The first subsystem is designed to capture and digitize electrical signals from sensors or other equipment. These data are then sent to the second subsystem which processes the waves and obtains the electrical values of interest from the samples received.

The third and final subsystem stores the parameters of interest and processed waves. Monitoring of real-time electrical parameters and the display of historical data stored by the user is also done at this point. Finally, it executes the management and detection of events and programmed alarms. This block consists of a web server and a database over which the web application is run to manage the information generated by the processing subsystem.

III. Implementation

A. Web application

The web application is the most important part of the user´s interaction with the system. As noted above, one of the main efforts during development is to provide an easy and complete use of the system for both expert and occasional domestic users.

The internal design is mainly based on patterns and highly modular design methodologies that allow the clear division between data, the mechanisms through they are managed and their display on the screen as well as ease of modification and expansion of functionality.

New web technologies, increasingly used in modern society, the implementation of simple design patterns and the appropriate use of visual language help to achieve this goal [26]. This technology would also increase accessibility to the system, providing it with multi-platform capabilities which allow the user to access the system from any device with a web browser.

For its development, the new web standards HTML5 and CSS3 have been used, respectively, as web modeling and style definition languages as recently proposed by the W3C. These technologies, coupled with standard scripting language Javascript and AJAX technology create a clear, simple and dynamic interface, giving the user the feeling of being in front of a desktop application where notifications and updated values can be obtained automatically and in real-time.

The web application consists of four different parts:

- **Main page** [see figure 2]: This page provides real-time relevant information from the facility and its monitored receptors. It consists of a dashboard that provides information on energy consumption, general electrical parameters, billing and CO_2 emissions of the entire system using real-time updated meters, a section with the last warnings and events in the system, a control panel for starting and stopping the system and an individual information viewer at the receptor level.
- **Analysis**: It provides several query tools for obtaining coefficients and electrical parameters of interest at general and receptor levels, showing detailed and interactive graphs for any registered period of time.
- **Warnings**: It shows the warnings produced by the processing subsystem as well as the events and variations detected during the processing. Queries can be made during custom time intervals at the receptor level.
- **Settings**: It allows easy configuration of the system through a wizard. It adapts to both new and advanced users by using different levels of detail.

Security is another important aspect of the system. The web application provides authentication and access control mechanisms to ensure that only authorized users can access the data. It also allows the granting of system reconfiguration privileges.

B. Hardware implementation

The system, as discussed above, is ready to be deployed on any platform. However, we have largely focused on advanced embedded architectures. These systems generally provide a great flexibility and computing power that make them ideal for a system such as this one.

The feasibility of implementing the system in an ARM embedded device after comparing it with the x86 architecture has been demonstrated in previous publications [27].

IV. System operation

The processing subsystem has a modular architecture, developed entirely in C language and run on Linux, in which there are different modules with independent objectives.

As shown in the block diagram [figure 3], the subsystem consists of the following modules:

- **Main module**: It is responsible for the sampling reception and the processing of each specific time interval. It stores some structures that contain timers that indicate the beginning of a new sampling reception through the acquisition modules.
- **Log module**: It is responsible for recording incidences and events detected during processing. This register is made at a database and log file level due to the necessity of registering the problems in the case of errors occurring in the database.
- **Module for the calculation of parameters of interest**: It hosts the methods for calculating the electrical parameters of interest from the coefficients provided by the execution of the analysis plugin used for this purpose.
- **Event detection module**: It analyzes the results obtained after processing the samples and detects, through several techniques, different events and variations such as overvoltages, temporary interruption of electricity supply or control of the total harmonic distortion values allowed.
- **XML Handler**: It contains methods for accessing and modifying XML files.
- **Plugin manager**: This module executes the loading, registration, initialization and system commissioning of the plugins defined in the configuration file.
- **Receptor manager**: It manages loading and data manipulation of the system receptors.

The sequence of actions performed is as follows:

1) **Argument capture**: It deals with the capture of arguments for parameters. It extracts the path to the configuration file.

Fig. 2. Screen snapshot of the web application.

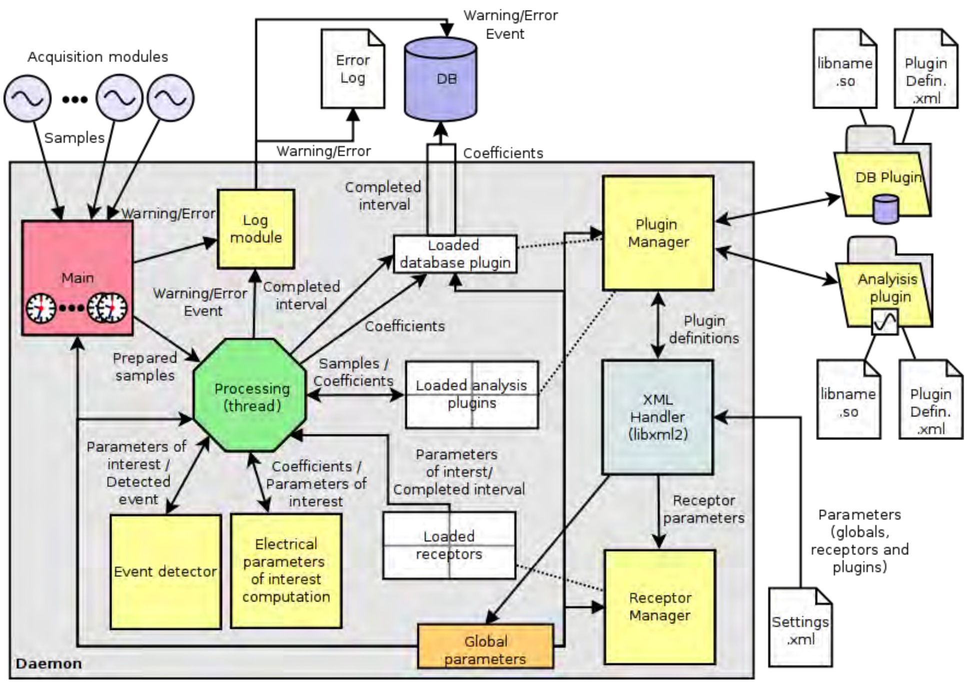

Fig. 3. Block diagram of the processing subsystem.

2) **Configuration file parsing**: A call is made to the

XML Handler module to create the node tree of the configuration XML document so that it can be run over in subsequent calls.

3) **Obtaining of global parameters**: The different global parameters of the configuration file are obtained by calling the XML Handler module.
4) **Calculation of global parameters derived**: Other derivatives that will be needed should be calculated by using the global parameters provided by the user through the configuration file. These are the number of samples in each processing interval, the cycle length and the number of cycles contained in a processing interval.
5) **Receptor load**: A call to the Receptor Manager is done in order to load the information of the receptors defined in the configuration file.
6) **General receptor load**: A call to the Receptor Manager is done in order to load the information of the receptors defined in the configuration file.
7) **Loading of analysis plugins**: A call to the Plugin Manager is done in order to load the analysis plugins defined in the configuration file.
8) **Loading of the database plugin**: The Plugin Manager is called in order to load the database plugin defined in the configuration file.
9) **Preparation of timers**: Once the system receptors have been read, the module creates several structures associated with each receptor that contain a timer and a structure to save the current timestamp. Each timer is armed to trigger at the time interval indicated in the configuration file. The following actions occur when the timer expires:
   a) **Sampling capture**: The system reads the acquisition module file from the final position of the last capture until obtaining the number of samples corresponding to the current processing interval. In case it is not possible to get all the samples of the interval after a reading, a time frame will be given for another sample reading. It will be considered that the acquisition module has been delayed if the elapsed delay time exceeds the limit set in the configuration file, interrupting the processing of the receptor. If recovery is successful, the delay time will be subtracted when resetting the timer for the next interval. This phase will be finished by updating the time stamp of the structure and resetting the timer.
   b) **Creation of processing thread**: After reading the samples, a processing thread for the current interval is launched in detached mode with respect to the main process, as it is not necessary to wait until it is finished. In this way, the resources occupied by the thread are immediately released. There is the possibility of creating more simultaneous threads as it is not conditioned by implanted thread limit imposed by the Kernel.
10) **Waiting for shutdown signal**: The daemon remains in a wait state for an interruption signal and timers, whenever they expire, are responsible for reading samples and creating new threads through asynchronous calls. The following actions are triggered if any shutdown signal is received from the main process:
   a) **Waiting for thread termination**: Some threads may still be processing when the interruption signal is received. At this moment, the resetting of all timers is interrupted and it is given a reasonable time for the threads finish what they are doing.
   b) **Closing the database**: When the time expires, the operating periods are closed in the database. The connection with the database is also closed.

Each processing thread executes a complete processing task of an interval corresponding to a receptor. This strategy allows the exploitation of some platforms´parallel processing capabilities at the expense of the implementation of multiprocessing techniques and synchronization mechanisms. Another advantage is that while performing operations to be executed following a sequential order to avoid errors, other processing threads corresponding to subsequent processing intervals can perform other tasks at the same time.

A processing thread is, firstly, responsible for the cycle RMS of voltages and currents. Then, it executes the different processing methods, coded as a plugin, that have been defined in the configuration file. The implementation of these plugins provides information on harmonics and interharmonics to be also used for the calculation, even at a level of frequency groups defined in standards such as IEC-61000-4-7 [28], of electrical values of interest such as the total harmonic distortion, RMS values, power factor or active, reactive and apparent powers.

Once the basic processing is finished, the aggregation of values in the time intervals defined by the user is performed. Finally, the storage in the database of the harmonics, interharmonics, cycle RMS and the processing intervals completed are stored in the database.

V. Conclusions

PQ is a study area of great interest to the scientific community that has received much attention in recent years. It is a very complex problem as it covers different fields of engineering and lacks a single solution. There is a great variety of techniques that attempt to provide quality solutions to identify and analyze the different events and problems that emerge in PQ.

Due to the importance of the problem, many commercial tools have been designed and put into the market to analyze and monitor PQ. However, while these tools present good characteristics and performance, they are usually very expensive. Furthermore, one of the main disadvantages is the use of closed protocols resulting in tools that are neither scalable nor interoperable with other systems.

The innovation of our work is the development of a completely free tool that can be used without any license restrictions. It also makes use of free software and standard technologies so that it can interoperate with other systems using international standard protocols recognized by the IEEE, IEC, ETSI, etc. This tool makes use of the latest analysis and monitoring techniques described in the bibliography (e.g. Wavelet, Kalman filters, etc.) Its modularity allows other developers to contribute their knowledge through API that interact with the system to expand its potential. On the other hand, the use of web technologies such as HTML5, CSS3 or JavaScript, open source DB such as MySQL or PostgreSQL and powerful programming languages such as C, make the system very reliable, scalable, visual and intuitive to use.

Furthermore, it is possible to build PQ monitoring systems with metering and billing capabilities if low-cost embedded systems and smart sensors are used.

ACKNOWLEDGEMENT

This work has been partly financed by the Spanish Ministry of Science and Innovation (TIN2008-01117), the Spanish Ministry of Science and Technology (AGL202-04251-C03-03) and the Andalucian Regional Government, Junta de Andalucía, via Excellence Project (P07-TIC02988).

REFERENCES

[1] A. B. Baggini, *Handbook of power quality*. Chichester, England ; Hoboken, NJ: John Wiley & Sons, 2008, edited by Angelo Baggini.; Includes bibliographical references and index.

[2] Cenelec, *EN 50160: Voltage characteristics of electricity supplied by public distribution systems*. Brüssel: Cenelec, 1999, "EN 50160"; Erstatter 1994-utgaven; 690: Elektrisitetsforsyning.

[3] IEC, *IEC 61000-4-30: Electromagnetic compatability (EMC). Testing and measurement techniques. Power quality measurement methods*. Brüssel: BSI, 2009.

[4] "IEEE recommended practice for monitoring electric power quality," *IEEE Std 1159-2009 (Revision of IEEE Std 1159-1995)*, pp. c1 –81, 26 2009.

[5] R. Arseneau, Y. Baghzouz, J. Belanger, K. Bowes, A. Braun, A. Chiaravallo, M. Cox, S. Crampton, A. Emanuel, P. Filipski, E. Gunther, A. Girgis, D. Hartmann, S.-D. He, G. Hensley, D. Iwanusiw, W. Kortebein, T. McComb, A. McEachern, T. Nelson, N. Oldham, D. Piehl, K. Srinivasan, R. Stevens, T. Unruh, and D. Williams, "Practical definitions for powers in systems with nonsinusoidal waveforms and unbalanced loads: a discussion," *Power Delivery, IEEE Transactions on*, vol. 11, no. 1, pp. 79–101, 1996.

[6] M. Bollen, "Voltage sags and interruptions," 1999.

[7] L. Angrisani, P. Daponte, M. D'Apuzzo, and A. Testa, "A measurement method based on the wavelet transform for power quality analysis," *Power Delivery, IEEE Transactions on*, vol. 13, no. 4; described in detail. Finally, some case-studies are examined in order, pp. 990–998, 1998.

[8] P. K. Dash, B. K. Panigrahi, and G. Panda, "Power quality analysis using s-transform," *Power Delivery, IEEE Transactions on*, vol. 18, no. 2, pp. 406–411, 2003.

[9] O. N. Gerek and D. G. Ece, "An adaptive statistical method for power quality analysis," *Instrumentation and Measurement, IEEE Transactions on*, vol. 54, no. 1, pp. 184–191, 2005.

[10] S. Santoso, E. J. Powers, W. M. Grady, and P. Hofmann, "Power quality assessment via wavelet transform analysis," *Power Delivery, IEEE Transactions on*, vol. 11, no. 2, pp. 924–930, 1996.

[11] N. Senroy, S. Suryanarayanan, and P. F. Ribeiro, "An improved hilbert–huang method for analysis of time-varying waveforms in power quality," *Power Systems, IEEE Transactions on*, vol. 22, no. 4, pp. 1843–1850, 2007.

[12] S.-H. Cho, G. Jang, and S.-H. Kwon, "Time-frequency analysis of power-quality disturbances via the gabor–wigner transform," *Power Delivery, IEEE Transactions on*, vol. 25, no. 1, pp. 494–499, 2010.

[13] G. T. Heydt, P. S. Fjeld, C. C. Liu, D. Pierce, L. Tu, and G. Hensley, "Applications of the windowed fft to electric power quality assessment," *Power Delivery, IEEE Transactions on*, vol. 14, no. 4, pp. 1411–1416, 1999.

[14] L. F. Auler and R. D'Amore, "Power quality monitoring controlled through low-cost modules," *Instrumentation and Measurement, IEEE Transactions on*, vol. 58, no. 3, pp. 557–562, 2009.

[15] R. Bernardes and F. Ayello, "Pqms - power quality monitoring system: Improve power systems through ieds," in *Electricity Distribution - Part 1, 2009. CIRED 2009. 20th International Conference and Exhibition on*, 2009, pp. 1–4.

[16] D. Divan, G. A. Luckjiff, W. E. Brumsickle, J. Freeborg, and A. Bhadkamkar, "A grid information resource for nationwide real-time power monitoring," *Industry Applications, IEEE Transactions on*, vol. 40, no. 2, pp. 699–705, 2004.

[17] M. Zhang and K. Li, "A power quality monitoring system over the internet," in *Information Science and Engineering (ICISE), 2009 1st International Conference on*, 2009, pp. 1577–1580.

[18] B. E. Kushare, A. A. Ghatol, and S. Kala, "Development of web based power quality monitoring system for handling user custom power quality query and auto power quality monitoring report notification via email," in *Information and Communication Technology in Electrical Sciences (ICTES 2007), 2007. ICTES. IET-UK International Conference on*, 2007, pp. 1–7.

[19] PQSoft. Top, the output processor. [Accessed: Feb. 2011]. [Online]. Available: http://www.pqsoft.com/TOP

[20] P. Laplante, A. Gold, and T. Costello, "Open source software: Is it worth converting?" *IT Professional*, vol. 9, no. 4, pp. 28–33, 2007.

[21] G. Ltd, "Benefits of using open source software," p. 1, 2010 2010.

[22] J. O. Smith, *Mathematics of the Discrete Fourier Transform (DFT): with Audio Applications*. Standford, Calif.: W3K Publishing, 2007.

[23] S. W. Smith, *The scientist and engineer's guide to digital signal processing*. San Diego, Calif.: California Technical Pub., 1997, by Steven W. Smith.; Includes index.

[24] D. Lee, P. Voumard, and N. Mani, "Condition monitoring of electrical equipment using wavelet analysis," in *Systems, Man, and Cybernetics, 1998. 1998 IEEE International Conference on*, vol. 1, 1998, pp. 811–816 vol.1.

[25] M. A. Mostafa, "Kalman filtering algorithm for electric power quality analysis: Harmonics and voltage sags problems," in *Power Engineering, 2007 Large Engineering Systems Conference on*, 2007, pp. 159–165.

[26] J. Nielsen, *Designing Web usability*. Indianapolis, Ind.: New Riders, 2000, jakob Nielsen.; Includes bibliographical references and index.

[27] F. G. Montoya, A. Alcayde, P. Sánchez, C. Gil, and J. Gómez, "Análisis comparativo de variables eléctricas en arquitecturas empotrados de alta prestaciones y x86 con gnu/linux," in *ACTAS DEL I SIMPOSIO EN COMPUTACIÓN EMPOTRADA SICE 2010*, 2010, pp. 177–184.

[28] IEC, *IEC 61000-4-7: Electromagnetic compatability (EMC). Testing and measurement techniques - General guide on harmonics and interharmonics measurements and instrumentation, for power supply systems and equipment connected thereto*. Geneva: CEI-IEC, 2002.