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Use of Smart Sensors in the Measurement of Power Quality

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Abstract: Today's businesses depend heavily on electrical services for lighting, general power, computer hardware and communications hardware. With the generalized use of sophisticated electronic devices, industries are shifting toward almost entirely electronic IT systems. PQ events are of increasing concern for the economy because today's equipment, particularly computers and automated manufacturing devices, is highly sensitive to such imperfections. Traditionally the control and supervision of a plant distribution network has mainly been focused on the protection of the network. Relatively little attention has been focused on the quality of the electrical energy. Metering technologies and communications systems have advanced to enable the development of web-based sensors. Power Quality is one area where these smart sensors can be very valuable. This paper investigates the challenges and possibilities in the development of distributed PQ measurement systems. This paper describes the challenges and lessons learned from this work. *Copyright © 2008 IFSA.*

Keywords: Smart sensors, Power quality, ADE7756

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1. Introduction

Assessment of Power Quality (PQ) and power disturbances involves looking at electromagnetic deviations of the voltage or current from the ideal single-frequency sine wave of constant amplitude and frequency. A consistent set of definitions can be found in [1]. The quality of the power supply delivered by utilities varies considerably and depends on a number of external factors. Things like lightning, industrial premises which apply and remove large loads, non-lineal load stresses, inadequate or incorrect wiring and grounding or short circuits caused by animals, branches, vehicular impact and human accidents involving electric lines. Some power providers seek to determine compliance with limits established in standards such as [2].

Sustained interruptions, which occur when voltage falls to zero for more than one minute, are the reliability problem with which most electricity consumers have the greatest direct experience and are the key phenomena measured in traditional utility service quality and reliability statistics. Indices such as and System Average Interruption Frequency Index (SAIFI) and Customer Average Interruption Duration Index respectively (CAIDI), do not capture PQ perturbations.

Among all categories of electrical disturbances, the voltage sag (dip) and momentary interruption are the nemeses of the automated industrial processes [3]. Voltage sag is commonly defined as any low voltage event between 10 and 90 percent of the nominal RMS voltage lasting between 0.5 and 60 cycles. On the other hand, voltage swell (which are not so common) do not normally disrupt sensitive load, but can cause harm to equipment. Momentary voltage interruption is any low-voltage event of less than 10 percent of the nominal RMS voltage lasting between 0.5 cycles and 3 seconds. Voltage sags can be caused by natural events (e.g., trees falling on power lines or lightning striking lines or transformers), utility activities (e.g., routine switching operations or human error), or customer activities (e.g., starting of large motors). Voltage sags at a customer bus are different depending to his location in the electrical network [4]. Because of the short duration of these PQ events, residential customers are rarely aware that a PQ event has taken place. However, for many industrial customers, they pose a far more significant problem than outages because of their much greater frequency of occurrence and overall because of that their incidence can cause hours of manufacturing downtime [5].

There are several conditioning solutions to voltage regulation, which are currently available in the marketplace. Among the most common are Uninterruptible Power Supply systems. Recently, new technologies like Custom Power devices based on power electronic concepts have been developed to provide protection against PQ problems [6].

The IEC 61000-4-30 has been established to define the methods for measurement and interpretation of PQ parameters. For each relevant type of perturbation is described a measurement method. It exits two different classes of measurement devices according to the precision given. Class A devices are used when precise measurements are necessary. For example, for contractual applications, verifying compliance with standards, resolving disputes, etc. Class B measuring instruments are used to determine statistical values and regulate/correct errors (troubleshooting).

The main characteristics and trends in advanced PQ measuring instruments can be found in [7-8]. Last years some experimental solutions have been proposed. In [9] the system is implemented by the use of standard LabView TCP/IP technology on a partial building low-voltage network that could be a simplified representative model of larger networks. As before, the system hardware in [10] consists of several PCs, each one hosting a data acquisition (DAQ) board, linked to the power system by a voltage transducer. The software implements different Virtual Instruments, using the well known NI LabView graphical programming language. Moreover, many utilities presently utilize dedicated PQ monitoring devices on the high and medium voltage stations to detect power quality events [11]. One of the milestone approaches was originally developed for the Electric Power Research Institute in the last decade [12]. However, the most widely extended infrastructure installed up to now is [13]. On the other hand, many automated factories presently utilize dedicated PQ measurement devices but on the point of common coupling and with the exclusive purpose of determining the utility responsibility in PQ events.

Little empirical research, however, is available from the perspective of integrating distributed measurement inside the plant. In brief, is needed a low-cost system capable of observing PQ phenomena on a continuous basis. This is imperative since most of the hidden cause come from unlikely sources such as operation of existing factory equipment or incorrect wiring schemes. While all major events can be captured, this could result in excessive data from non-critical events. The maintenance engineer must then sort through this data to analyze the PQ disturbance. Manual methods are expensive, time consuming, and error prone. Custom software developed for each site for analyzing data, again, can be very expensive to develop, maintain, and-depending on their underlying architecture-difficult to expand. Thus, designing a system that has the ability of analyzing, condensing and interpreting voluminous raw data so that levels can be assessed against limits and can be easily expanded would become the most significant challenge in the PQ measurement arena. This paper introduces an innovative PQ web-based measurement system, which is suitable for continuous PQ measurement in an industrial or commercial plant.

2. Methodology

The PQ system presented here is a web-based measurement and alarm system that relies on widespread deployment of a large number of low-cost sensors, termed “PQ watch”, throughout the distribution network of the plant. The monitors continuously measures energy consumption information as well as detailed data on PQ events including outages, blackouts, brownouts, interruptions, and short-duration disturbances such as voltage sags and swells. In addition to these measurement functions, advanced functions for energy consumption savings and improving Energy-Use Diagnostics can be implemented in the system.

Developed web-based PQ measurement system makes it also possible to gather together all measured PQ data from various sites inside the plant. Data from “PQ watch” sensors allows us to identify PQ events and determine their impact on individual machines. In addition, because the data from all monitors are uploaded via the internet to a central database server, we can correlate data from multiple monitors to determine whether events recorded at one site were detected or had impact elsewhere. From this information, we will determinate the origin and cause of the event and the effect of the event on company processes, including cost of downtime, drawing finally conclusions about the responsibility of the utility.

PQ disturbances can range from high frequency impulses caused by lightning strikes, to long-term sustained overvoltages resulting from poor voltage regulation. The capabilities of the measurement device will also influence the choice of which parameters to measure. Broadly speaking, these sensors must be able to meter the following quantities: voltage and current, active power, apparent power, total reactive power, fundamental frequency reactive power, energy use, cost of power, power factor, total harmonic distortion of the supply voltage (THD), also the nine most important harmonic voltages, frequency of the supply voltage and voltage unbalance between the three phases. In addition, voltage swell, sag and interruptions. The recording density could be set as some seconds, minutes or hours. The simplest version of the PQ monitor would record only aforementioned powers, voltage and current variations.

The development of PQ measurement in automates factories requires first of all distinguishing between online and offline analyses:

Online analysis is devoted to the incidents that need immediate attention (for example sags or interruptions). The online data analysis can be performed within the instrument itself or immediately upon collection of the information at a central processing location. In order to reduce the data overburden the event should be grouped in categories such as transient, interruption or voltage sag or swell. As exist the possibility of receiving several incident alarm at the same time, it could be necessary the use of some kind of “distribution scoreboard” algorithm that automatically classifies events in rank of importance. This could be done by the use of different criteria, i.e. maximal time duration, maximal magnitude variation or maximal energy variation.

On the other hand, the offline PQ analyses the information that usually have been included in a PQ report, for example:

- Statistics of the steady-state Variations (voltage level, harmonics, unbalance, or flicker),
- Statistics of the Event resulting from incidents (sags, short-interruptions, swells, or transients),
- Identification of the likely cause of the power disturbances,
- Characterization of the electromagnetic compatibility level of equipments and installation,
- Recommendations for cost-effective mitigation and maintenance solutions.
-

In addition, it is necessary a scaled approximation in this reporting activity, differentiating between the detailed local approximation to a global point of view. Thus, the development of systematic procedures for PQ data management supports in general the reporting of distribution PQ surveys:

- Site report (e.g. detailing sufficiently the quality reports, planning of compensation of reactive power, instructions for the use of various equipment),
- Plant network report (e.g. giving simple site indices for all measurement point, for investment plans and management of voltage drops and other disturbances, and offering the ability to correlate events recorded at geographically dispersed locations)

3. Power Quality Sensor

Sensors can be classified into electrical, mechanical, thermal, radiation, optical, magnetic and chemical/biochemical sensors. Sensors are labelled as microsensor, nanosensor or simply sensor according to their physical dimensions. The boundaries between these different sensor types are flexible. In power measurement, sensor outputs can be voltage or current signals, which are traditionally associated with analog sensors. The outputted analogous signal is continuously pushed to a central control block for later processing through a shield cable. Going one step further appear digital sensors, these earlier solutions can read the analogous signal and transform it into a digital form for transmission. In industry a new tendency in the field of sensor application can be observed of getting more information from online sensor signal analysis. Though the digital sensors are capable of networking, they will bring heavy burdens to central servers to process data and network loads. Thus, both kind of sensor are called “dumb” sensor due to lack of the processing capability at the sensor site. Intelligence in the context of a sensor is not comparable with human intelligence. It indicates only that the sensor is different to one that supplies just the raw data. The term ‘smart’ is also used instead of the word ‘intelligent’.

Smart Sensor systems are composed of three parts: communications, data acquisition and sensors. It is today possible to have all three parts on a single chip at a low cost [14]. Compared to dump sensors, Smart sensors have their own “brains” and can make decisions by themselves. They usually output digital values in which the embedded microprocessor core may perform calibrations and scaling functions internally. Parameters that have an impact on the price of a smart sensor system are the number of sensors, the power supply choice, the communications nodes, the communications capabilities (one-way, two-way, always-on or not). However, the majority smart sensors in use today usually have a customized interface and are networked through a proprietary network, such as a Profibus or CANbus network. For historical reasons, these Fieldbus networks are proprietarily designed, and incompatible not only with each other but also with the widespread Ethernet [15].

There has been exponential growth of Internet use in recent years. This has generated a strong trend toward using Internet protocols, TCP/IP in particular, as a universal backbone for communications solutions. Internet communication provides nearly real-time access to sensor information over public networks. It possibilities a standards-based web services application, enabling simple integration to Java, .NET, or other web services aware applications and infrastructure. Internet appliances are expected to become almost ubiquitous in our environment within this decade. The sensor presented here can act as an embedded Web server [16]. The basic function of an embedded Web server is to pick up and accumulate data about the state of the sensor and bring in instructions from an operator. The data from these sensors can be viewed directly by a standard Web browser, used as client program, or imported directly into another system using XML data labels. This allows easy access to the sensor information by anyone on the enterprise-wide LAN.

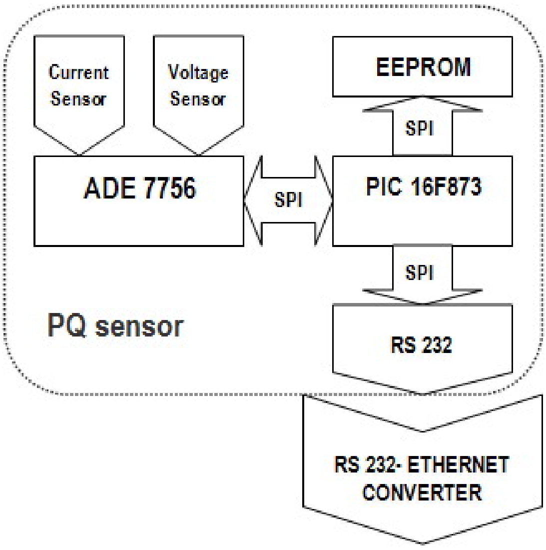

Fig. 1. PQ Sensor block diagram.

The distribution PQ measurement paradigm proposed is implemented in a smart sensor based on the ADE7756 integrated circuit from Analog Devices. The data sheet provides detailed information on the functionality of the integrated circuit [17]. The ADE7756 is a high-accuracy electrical power measurement integrated circuit with a serial interface. The ADE7756 incorporates two second-order sigma-delta ADCs, reference circuitry, temperature sensor, and a fixed DSP function for the calculation of active power and energy. A highly stable oscillator is integrated into the design to provide the necessary clock for the integrated circuit. Circuitry is provided to null out various system errors including gain, phase, and offset errors. Additional circuitry provides waveform sampling, programmable interrupts, and power line monitoring. The ADE7756 contains a sampled Waveform register and an Active Energy register capable of holding at least five seconds of accumulated power at full load.

The "PQ watch" sensor is comprised of the ADE7756, the PIC 16F873 microcontroller, an EEPROM, and an RS-232 converter integrated circuit. The ADE7756 provides the measurement for the system. The waveform sampling mode of the ADE7756 is used to process RMS calculation into the microcontroller. The microcontroller provides control of the meter as well as communications. An EEPROM is used to store various calibration parameters of the meter and store the meter's data during a power-down.

Fig. 2. Prototype board developed.

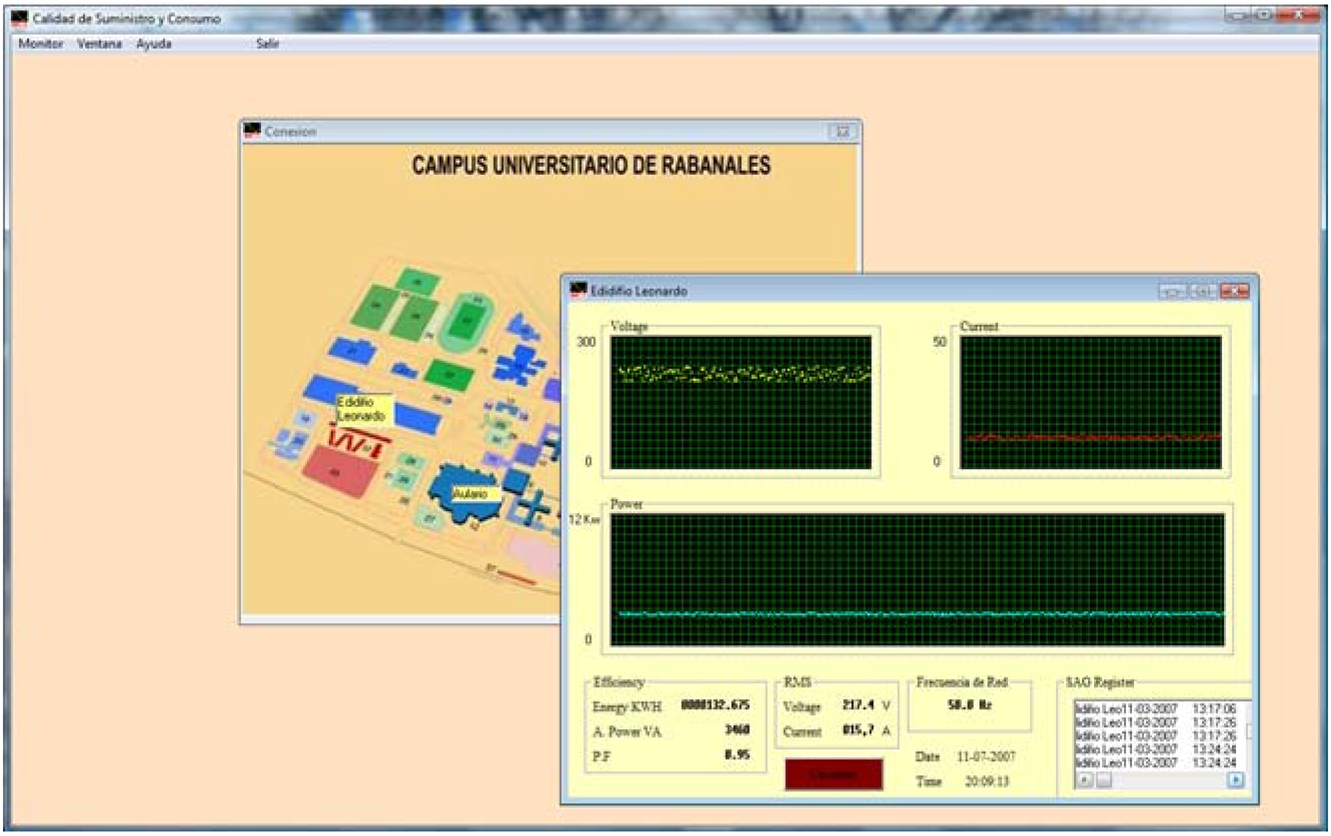

Fig. 3. System web page showing information from active site.

This low cost PQ meters cannot afford any programmable DSP component. The actual sensor developed in this experience belongs to the simplest *class B* version of the PQ monitor stated above, allowing PQ measurements for: sag, swell, number of over-current occurrences, number of power outages, duration and time of the last 8 power outages, maximum and minimum frequency, phase loss.

The limitation of a standard 8-bit microcontroller in signal computation ability leads to the choice of the fastest operating clock possible for the microcontroller. The maximum clock frequency for the microcontroller chosen is 20 MHz. The RMS computation implemented in our solution uses a square routine and some real-time signal processing. These routines should be performed between each sample. A quick evaluation of the time needed to process 16-bit samples at 20 MHz leads to a worst-case computation time of approximately 350 µs.

As shown in Fig. 1, the communication between the ADE7756 and the microcontroller is done through a serial interface (SPI). The SPI port provides access to all registers of the ADE7756 and allows the user to calibrate various components of the meter including gain, offset, and phase errors. This measurement IC also incorporates a detection circuit for short duration low or high voltage variations. The voltage threshold levels and the duration (number of half line cycles) of the variation are user programmable.

An external RS-232 port is also provided to the µC as the principal method to communicate through a dedicated communication bus to the embedded web server. This module is a stand alone Ethernet Server designed to connect industrial devices with serial interfaces to the Ethernet network using the TCP/IP protocol. It contains an Ethernet Server and RS-232/485/422 interfaces. The standard features include:

– Use standard Web Browser (TCP/IP protocol) or HTTPGET DOS program for network connectivity.
– Install via RS-232/485/422 serial port connection.
– Transfer data from RS-232/485/422 serial interface to TCP/IP using built-in socket server.
– Use a standard home page or customize web page using special applets, which are available on our website.

4. System Operation

The system provides the central “Web site control panel” for the entire collection of deployed sensors. Each user can register and configure the sensors, adjust sensitivity levels, and specify deployment location and email notification addresses.

The Web site also provides a number of ways to view data from single or aggregated monitors. To display the results of an analysis, the software will provide pages that may consist of trend plots, tables, or voltage events surveys. These surveys are a very common tool to obtain statistical information on the PQ performance of a site after a period of observation. The combined information obtained from these surveys gives a good impression of the quality of the supply in the facility [4]. This kind of diagram is known as a magnitude-duration scatter plot. It also translates information from the well-known Information Technology Industry Council (ITIC) curve, formerly named Computer Business Equipment Manufacturer’s Association (CBEMA) curve. The curve establishes magnitude and duration limits within which input voltage variations do not affect the reliability of the electronic equipment.

Furthermore, when all users are on the same LAN, static HTML reports can be generated and posted on the server. Users can access these reports by entering the Web address for the report in a standard Web browser. For real-time or near-real-time data reports, the user must need immediate access to the data for diagnostics. An ASP could automatically generate and “push” reports to users through e-mail. This approach can be also useful when a user would like to have a daily report showing performance on the previous day or if a monthly report is desired.

As usual, when coexist tens and sometimes hundreds of measurement points in the distribution network of the plant it must be prescriptive to structure the data contained in these measurements. A file format for PQ data interchange must be sufficiently flexible to encompass the diverse classes of perturbations that must be represented. The most popular format is the IEEE Std 1159.3-2002 Power Quality Data Interchange Format (PQDIF). It provides a compact, flexible, extensible and neutral platform to exchange these diverse measurements between different PQ instruments and software applications [18]. PQDIF is a binary format that is optimized to minimize disk storage and transfer time. However, when the ease of data manipulation is more important than file size, an alternate easily-parsed, human readable, text-based representation of PQDIF has been proposed by representing any PQDIF file in Extensible Markup Language (XML) [19].

Finally, in an enterprise system, an embedded system gateway can be used to push data to a password-protected website. This allows users at multiple locations who are not on the same LAN to access these reports.

5. Conclusions

PQ is a complex domain, covering over a dozen problem areas. At present, most energy-intensive facilities suffer to a certain degree from poor power quality, while most sites have already adopted some solutions. However, there is no single solution.

Common voltage events not only stops production but can also affect the performance of the equipments integrated in a highly automated process, which directly impact the quality of the product. In each occasion, the equipment must be restarted, and in some cases re-programmed or repaired before production can resume.

Traditionally the control and supervision of a plant distribution network has mainly been focused on the protection of the network. Relatively little attention has been focused on the quality of the electrical energy. Nowadays one of the most popular and general technologies for information resources access and information representation is the World Wide Web technology (Web technology) which is widespread in the global computer network Internet. Metering technologies and communications systems have advanced to enable the development of web-based sensors. PQ is one area where these smart sensors can be very valuable. The sensors developed here are significantly less expensive than conventional PQ monitors (€500-600 per device compared to €5,000-10,000 for conventional PQ monitors). More importantly, the system's low cost per node means that the presence of a large number of monitors can be financially feasible than it has been in the past. In addition, the reliance on standard web browsers eliminates the need for the significant investment in software and hardware infrastructure that is typically required for other measurement systems.

References

[1]. Moreno-Muñoz, A., Power Quality: Mitigation Technologies in a Distributed Environment, *Springer*, 2007.

[2]. EN 50160, Voltage characteristics of electricity supplied by public distribution systems, 2000.

[3]. IEEE guide for servicing to equipment sensitive to momentary voltage disturbances, *IEEE std*., 1250, 1995.

[4]. Moreno-Muñoz A., Redel M. D., González M., Power quality in high-tech campus: a case study, Proceedings of the Institution of Mechanical Engineers, Part A, *Journal of Power and Energy*, 220, 3, 2006, pp. 257 – 269.

[5]. Moreno-Munoz A., Pallarés V., Galisteo P., De-la-Rosa J. J. G., Study of voltage sag in a highly automated plant, *In Proceedings of the IEEE MELECON*, 2006, 1060-1063.

[6]. Moreno-Munoz A., Oterino D., González M., Olivencia F. A., De-la-Rosa J. J. G., Study of sag compensation with DVR, *In Proceedings of the IEEE MELECON*, 2006, pp. 990-996.

[7]. Mark F. McGranaghan and Surya Santoso, Challenges and Trends in Analyses of Electric Power Quality Measurement Data, *EURASIP Journal on Advances in Signal Processing*, Vol. 2007, 2007, Article ID 57985.

[8]. Balcells, J., Parisi, V., Gonzalez, D., New trends in power quality measuring instruments, *IEEE IECON 02*, Vol. 4, 2002, pp. 3344 - 3349.

[9]. Cristaldi, L., Ferrero, A., Salicone, S., A distributed system for electric power quality measurement, *IEEE Transactions on Instrumentation and Measurement*, Vol. 51, Issue 4, 2002, pp. 776 – 781.
[10].Bucci, G., Fiorucci, E., Landi, C., Digital measurement station for power quality analysis in distributed environments, *IEEE Transactions on Instrumentation and Measurement*, Vol. 52, Issue 1, 2003, pp. 75 – 84.
[11].Pauli, S., Krahl, B. O., Leuschner, B., Know your power, *IEEE Industry Applications Magazine*, Vol. 11, Issue 2, 2005, March-April, pp. 21 - 30.
[12].M. McGranaghan, Trends in power quality Monitoring, *IEEE Power Engineering Review*, Vol. 21, Issue 0, 2001.
[13].Divan, D., Luckjiff, G. A., Brumsickle, W. E., Freeborg, J., Bhadkamkar, A., A grid information resource for nationwide real-time power monitoring, *IEEE Transactions on Industry Applications*, Vol. 40, Issue 2, 2004, pp. 699 - 705.
[14].Middelhoek S., Celebration of the tenth transducers conference - The past, present and future of transducer research and development, *Sensors and Actuators A: Physical*, Vol. 82, No. 1, 2000, pp. 2-23.
[15].Bo Tao, Han Ding and Y. L. Xiong, Design and implementation of an embedded IP sensor for distributed networking sensing, *Sensors and Actuators A: Physical*, Vol. 119, Issue 2, 2005, pp. 567-575.
[16].Riihijarvi, J., Mahonen, P., Saaranen, M. J., Roivainen, J. and Soininen, J. P., Providing network connectivity for small appliances: a functionally minimized embedded Web server, *IEEE Communications Magazine*, Vol. 39, Issue 10, 2001, pp. 74-79.
[17].Active Energy Metering IC with Serial Interface ADE7756 Data Sheets (http://www.analog.com).
[18].Chen, S., Open design of networked power quality monitoring systems, *IEEE Transactions on Instrumentation and Measurement*, Vol. 53, Issue 2, 2004, pp. 597- 601.
[19].Dabbs, W. W. and Sabin, D. O., Representation of IEEE Std 1159. 3-2002 PQDIF in extensible markup language, XML, *IEEE Power Engineering Society 2004 General Meeting*, 6-10 June 2004, Vol. 1, 2004, pp. 510- 515.

Guide for Contributors

Aims and Scope

Sensors & Transducers Journal (ISSN 1726-5479) provides an advanced forum for the science and technology of physical, chemical sensors and biosensors. It publishes state-of-the-art reviews, regular research and application specific papers, short notes, letters to Editor and sensors related books reviews as well as academic, practical and commercial information of interest to its readership. Because it is an open access, peer review international journal, papers rapidly published in *Sensors & Transducers Journal* will receive a very high publicity. The journal is published monthly as twelve issues per annual by International Frequency Association (IFSA). In additional, some special sponsored and conference issues published annually.

Topics Covered

Contributions are invited on all aspects of research, development and application of the science and technology of sensors, transducers and sensor instrumentations. Topics include, but are not restricted to:

- Physical, chemical and biosensors;
- Digital, frequency, period, duty-cycle, time interval, PWM, pulse number output sensors and transducers;
- Theory, principles, effects, design, standardization and modeling;
- Smart sensors and systems;
- Sensor instrumentation;
- Virtual instruments;
- Sensors interfaces, buses and networks;
- Signal processing;
- Frequency (period, duty-cycle)-to-digital converters, ADC;
- Technologies and materials;
- Nanosensors;
- Microsystems;
- Applications.

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