METROLOGY AND MEASUREMENT SYSTEMS
VOL. XIV, NUMBER 4 (2007)

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A MULTI-DSP BASED INSTRUMENT FOR REAL-TIME ENERGY AND PQ MEASUREMENTS

The evaluation of electrical energy flows is at the base of all operations connected to commercial transactions on the energy market. Typically, the measurement apparatuses are made and characterized to work in ideal sinusoidal conditions. But, with increasing diffusion of power electronic devices, the typical characteristics of a power network are far from sinusoidal ones. With the aim to link the cost of energy to the level of power quality, it is necessary to determine the energy but also the indexes which characterize the power quality. In this paper the design and implementation of a multi-processor measuring instrument based on multiple digital signal processors (DSPs) is discussed. This system can embody a number of special signal processors and analog I/O modules, specifically designed to obtain the flexibility and scaling ability to meet the needs of real-time measurement applications and low cost. After a prototype description, part of the analysis algorithm is reported. The paper is completed by preliminary results of metrological characterization.

Keywords: power quality, real time measurement, multi-digital signal processor

1. INTRODUCTION

Electrical energy measurement plays a crucial role not only in commercial energy transactions but also in the estimation of energy balances in industries and in the performance evaluation of machines and energy systems, both traditional and innovative. With the integrated quality certification of the electrical services the possibility has been introduced of stipulating contracts for quality for the customers who receive high and medium voltage and for electrical energy distribution companies. This implies the fixation of an agreed level of quality ("Custom Power"), an annual fee on the back of the customer and a reimbursement in favour of him in the case when the level of quality has not been respected. This requires real-time determination of energy flows and a corresponding level of quality. In order to reach this goal, digital signal processing techniques can be adopted; these techniques are commonly used in today's instrumentation world, both in the scientific and industrial fields. They are mainly based on the application of mathematical operations to digital samples representing physical-world signals.

Most measurement algorithms, such as the discrete Fourier transform, digital filtering, or adaptive signal processing, require the extended use of arithmetic operations of multiplication and addition. A suitable processor for these applications is the DSP, thanks to its special architecture that accelerates the execution of numerically intensive calculations. In fact it performs multiply-accumulate (MAC) operations for each single clock cycle, while general purpose processors generally require tens of clock cycles for a multiplication. Instruments for real-time measurements are characterized by an absolute time constraint for completing input, processing and output operations, which must not be exceeded. They are specifically designed to reduce:

- the time spent by the data acquisition system (DAS) to acquire the input signal and send out data;
- the time spent by the microprocessor to process data;
- the time spent to transfer data to the DAS and to generate an output signal, in case the system must supply analog responses.

Data processing time mainly depends on the required parameters, that is, on the adopted measurement algorithm and on processor performance. High-performance systems are generally based on multi-DSP, to provide enough flexibility and scaling ability to meet system constraints at relatively low costs. In these systems, each DSP conducts a portion of the signal processing, concurrently to the other processors [1, 2]. In the last years new microcontrollers with Harvard architecture are on the market; they allow to achieve low cost and moderately high performance.

In this paper we are mostly concerned with the design and implementation of a multi-DSP instrument designed for real-time measurement of energy and power quality. In the designed equipment the Microchip DSPic30F3013 has been adopted.

As the measurement algorithm is concerned, a real-time implementation of a recursive on-line spectral measurement of input signals, e.g. voltage and current in a power circuit has been employed.

In the paper some hardware and software issues associated with the design and implementation of the system are reported. Finally, the first obtained results, related to the investigation of the dynamic behaviour of the system, are presented in order to highlight the achievable accuracy.

2. MEASUREMENT INSTRUMENT

The greatest difficulty for the designer of instrument for real-time applications is that the DSP overall computing power is not high enough to satisfy the real-time constraints. In fact, apart from the DSP throughput, it must be also considered if the specific requirements, in terms of data flow, can be ensured by the memory and I/O architectures. Some devices are optimized for operation from on-chip memory, even if it is strictly limited. Better performance can be achieved by DSPs equipped with multiple external memory buses that enable the processor to load multiple operands, such as data samples, simultaneously and in parallel with an instruction.

In a measuring instrument this is not enough, because data must come from external devices, such as transducers. This means that an I/O subsystem with a suitable interface for handling inputs from the A/D array must be included. The high sample rate available from high-speed data acquisition systems (DASs) is generally obtained by using local FIFO memories to buffer the data. Sample words can then be quickly read out by the DSP in block transfer. However, although high transfer rates are declared, the time between initiating a request for data and the beginning of the actual data transfer (latency) may be very long. For the applications that require frequent short data transfers, the latency time may be a fundamental parameter. This is the case of processing new data every clock cycle, as required by recursive measurement algorithms.

2.1. Hardware implementation

The measurement system is composed by three multi-DSP sections, one for each voltage phase. A new kind of microcontroller dsPIC 16Bit Digital Signal Controller (DSC) is adopted in order to implement the data acquisition and pre-processing. These dsPIC devices reach speeds up to 30 MIPS and are very efficient for C programming. The dsPIC30F family of devices combines the high instruction throughput with true DSP capabilities, such as single cycle 16-bit multiply and zero overhead looping. This microcontroller has 20 I/O ports, 2048B SRAM, 1024B EEPROM, 24kB Program (FLASH), 12-bit A/D converters 100kSps, multiple serial interfaces including CAN, UART, SPI, and I2C. After pre-processing of acquired samples the DSC Microcontrollers exchange the data with a 18f2455 PIC Microcontroller through a parallel bus; thanks to this Microcontroller it is possible to implement the connection with the microkernel embedded Linux board through a RS232 or USB interface. The simple acquire and pre-processing multiprocessor system's block diagram is showed in Fig. 1.

The system is able to mount USB mass storage device which stores SQL data base with measurement results. The Linux board has the task of:

- managing the communication with the different multiprocessor devices, through the serial port;
- data post processing;
- managing and storing the data in DB;
- managing remote communications as a server;
- publishing the results [5].

The complete system is shown in Fig. 2. Moreover, a Linux embedded board stores received information in a date base on an USB mass storage device and publishes it, on demand, through one or more network interfaces connected to the system (i.e. GPRS/UMTS, WiFi, Ethernet).

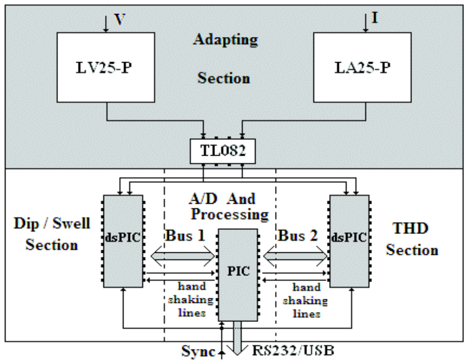


Fig. 1. Multiprocessor system.

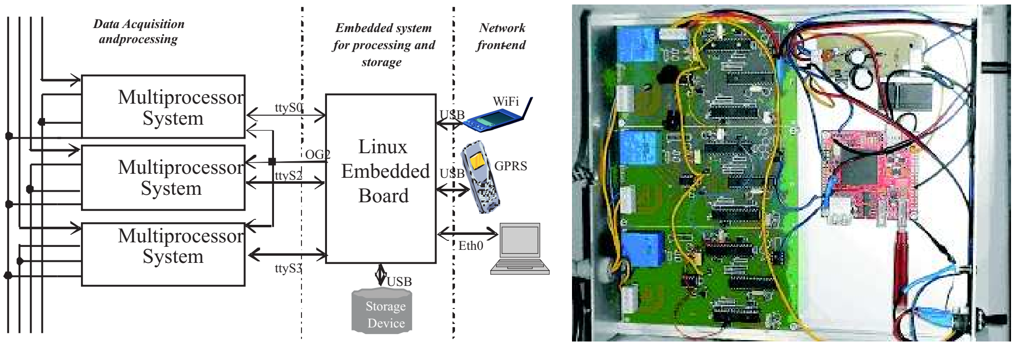


Fig. 2. MultiDSP implemented system.

2.1.1. Linux Embedded board

For network connectivity and web server applications, a low cost embedded system for developing Internet devices called Fox board has been used. Fox is a small board with Linux micro-kernel. It is based on the ETRAX LX100 MCM processor with 4MB program memory and 16MB data memory. Fox is useful either as a stand-alone device for network applications like micro web server, proxy, router, etc. or as a socket module to integrate into your own application board. ETRAX LX100 is a 32bit RISC CPU at 100MIPs whit on chip Ethernet interface (10/100 Mb/s) and 2 USB 1.1 port.

The Linux kernel is compiled on board with modules for http Server, FTP Server, SSH, SCP, TELNET Server and PPP support. Moreover it is possible to compile C application, make CGI and Data Base with SQL. In this way, the system is able to mount an USB mass storage device where measurement results can be stored in a SQL date base.

2.2. Software implementation

Two levels are generally adopted to describe the software structure of a multiprocessor system: the application software and the operating system (OS).

The application software is typically structured in processes, namely subprograms that communicate among themselves along link channels. Each subprogram can be independently designed and compiled, because its internal structure is not fundamental. Because in a multi-DSP instrument the processors can execute different portions of the algorithm, to increase the processor bandwidth, the gain realized is strictly related to a software schedule to insure that the DSPs are not waiting for each other.

Scheduling, input-output and process communications are supported by the OS. If the DSPs must execute several operations, as occurs on a multitasking system, a real-time operating system (RTOS) must be added, even if it increases the system complexity. However, in an instrument it is important to combine maximum control over the hardware with minimum run-time overhead. If the executed program will repeatedly perform a single sequential set of tasks, as typically occurs in a measuring instrument, a RTOS is not needed. In this application the problem of process cooperation and synchronization is solved by adopting the message exchange method: synchronization of the processes is achieved because it takes place when both the inputting and the outputting processes are ready: the process which first becomes ready must wait until the second is also ready.

The DSP board can perform a computation-intensive measuring algorithm, while the host processor can handle the physical display, data logging, storage, and the overall system control and configuration functions. In this way both hardware and software for most applications are readily available and then the designer can significantly reduce system development time and costs.

2.2.1. Synchronization handshake

During boot time, the Fox board synchronizes the start of acquisition of the three DSPs adopting a handshaking protocol. To implement this protocol, in addition to serial interfaces the digital output of the Fox board (OG2) connected to all the DSP has been used.

The adopted handshaking protocol is the following:

– after power on, all dsPICs wait that the Fox board is ready and raises OG2 logical value;
– each dsPIC reads the logical value and it sends a conventional string to the Fox;
– after reception of strings from all the dsPICs, the Fox board lowers the OG2 logical value;
– when OG2 becomes low, dsPICs begin acquisition and pre-processing operations.

Figure 3 shows the Synchronization Handshake Protocol; it is possible to see that the samples are sent after 3s, but this interval is adjustable by the user. In order to implement the communication of a flagging event, another handshaking protocol is implemented. If the event, such as dip, occurs during the monitoring, the second handshaking protocol is implemented as follows:

– every three seconds, the DSPs transmit the voltage RMS value;
– when the dip occurs, the DSPs send a flagged RMS value;
– after that, the Fox receives the flag, it waits for the min RMS value and the time duration of the dip;
– the DSPs send the min value and time duration of the dip until the event is ended;
– when the event is ended the DSPs return to send the voltage RMS value every three seconds.

A temporal diagram of the implemented flagged event protocol is shown in Fig. 4.

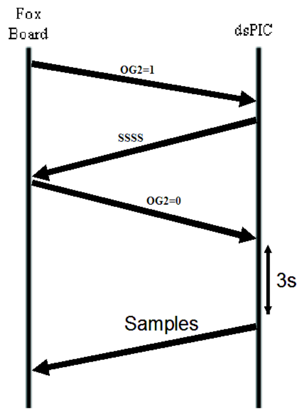


Fig. 3. Synchronization Handshake Protocol.

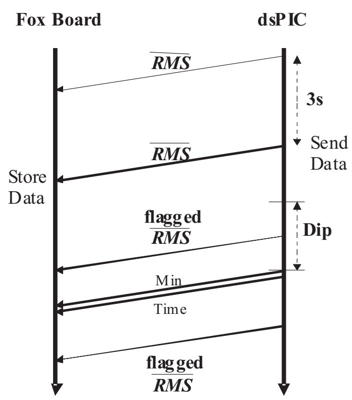


Fig. 4. Flagged event protocol.

2.2.2. Open Source Software Internet Platform

As a multipurpose operating system, Linux is used for a wide variety of purposes including networking, software development, as well as an end-user platform. Apache is an implementation of an HTTP server and it is the most popular Web server in use today. MySQL is an implementation of a database server that is known for its speed and reliability. PHP is general-purpose scripting language that is particularly suited to Internet-based system development and is the most widely used Apache module.

3. MEASUREMENT ALGORITHM

To be confident with the instrument performance, it has been applied for the spectral analysis of two distorted signals, e.g. voltage and current in a power circuit, by executing a recursive algorithm [3]. Each signal, periodically sampled, can be expressed as a sequence $s_n = \{s[n]\}$ with period M, and as a sum of M harmonically related complex exponential sequences (Fourier terms), described by the notation:

$$s_n = \sum_{\nu=0}^{M-1} s(\nu)\, e^{j\frac{2\pi}{M}\nu n}, \tag{1}$$

where $2\pi/M$ is the fundamental frequency associated with the sequence s_n. By considering the real (r) and imaginary (i) parts into (1) and replacing the Euler relation in the complex exponential terms, we obtain:

$$\begin{aligned} s_n &= s_n^{(r)} + j s_n^{(i)} = \\ &= \sum_{\nu=0}^{M-1} \left(S_\nu^{(r)} \cos\frac{2\pi\nu n}{M} - S_\nu^{(i)} \sin\frac{2\pi\nu n}{M} \right) + j \left(S_\nu^{(i)} \cos\frac{2\pi\nu n}{M} + S_\nu^{(r)} \sin\frac{2\pi\nu n}{M} \right). \end{aligned} \tag{2}$$

Because of the periodicity of (2), only the first half ($N = M/2$) of the frequency samples (positive frequencies) has been considered. The time-discrete space-state model of a real periodic signal with samples is given by the following stochastic difference equations:

$$\begin{cases} x_{n+1} = F x_n + G w_n \\ s_n^{(r)} = H x_n + v_n s_n^{(r)} \end{cases}, \tag{3}$$

where x_n (by order $2Nx1$) is the state-space vector, F ($2Nx2N$) is the system matrix, H ($1x2N$) is the output matrix, G is the noise input vector and $\{v_n\}$ and $\{w_n\}$ are assumed to be independent white noise processes, with zero mean and covariance Q_n and R_n respectively. A recursive algorithm for the space-state vector estimation of system (3), given the measurement, has been obtained by applying FRLS theory [3].

The magnitude A_ν and phase α_ν of the ν order signal harmonic, at each sampling time, is thus given by:

$$A_\nu = \sqrt{x(2\nu+1)^2 + x(2\nu+2)^2} \qquad \alpha_\nu = \tan^{-1}\left(\frac{x(2\nu+2)}{x(2\nu+1)}\right), \tag{4}$$

where $\nu = 0$ is the DC component.

Digital processing of these quantities allows the instrument to make quantitative measurements of a variety of parameters, to evaluate the impact of harmonics on the power system:

– the harmonic voltages V_ν and currents I_ν content;
– the voltage and current effective (RMS) values;
– their crest (ratio of peak to rms) factors;
– the mean power:

$$P = \sum_{\nu=0}^{N} V_\nu I_\nu \cos(\Phi_\nu), \tag{5}$$

where Φ_ν is the phase angle for sinusoidal excitation of ν^{th} harmonic frequency;

– the harmonic active power;
– the power factor:

$$\text{p.f.} = \frac{\sum_{\nu=0}^{N} V_\nu I_\nu \cos(\Phi_\nu)}{V_{rms} I_{rms}} = \frac{\sum_{\nu=0}^{N} V_\nu I_\nu \cos(\Phi_\nu)}{\sqrt{\sum_{\nu=0}^{N} V_\nu^2}\sqrt{\sum_{\nu=0}^{N} I_\nu^2}}, \tag{6}$$

– the THD (Total Harmonic Distortion), defined as the ratio of the effective value of the distorted signal, from which the fundamental component is eliminated, to the effective value of the original distorted signal [4];
– the fundamental frequency f_0.

4. CHARACTERIZATION RESULTS

In this section, some experimental results are shown. A measurement station for the characterization of the realized instrument has been built-up. It is composed of a signal generator, implemented in a CVI environment, that drive a Pacific Power source AMX3120. A reference wattmeter Norma D6100, made by LEM, with an accuracy of power measurement better than 0.1% is used to verify the signals generated. The measurement station is completed by the instrument under test. All the station is numerically controlled through an IEEE 488 bus.

Table 1. Electrical power test.

Phase angle	Active Power (kW)			Reactive Power (kVAR)		
rad	Refer.	measured	Deviat. (%)	Refer.	measured	Deviat. (%)
0	0.312	0.311	0.32	0	0.040	—
$\pi/4$	0.220	0.223	1.36	0.220	0.223	1.59
$\pi/2$	0	0.005	—	0.312	0.315	0.96
$-\pi/4$	0.220	0.219	0.45	0.220	0.219	0.45

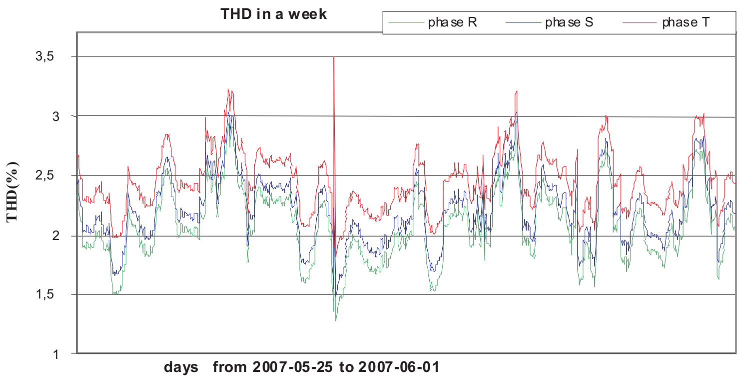


Fig. 5a. Three phase THD voltage monitoring in a week.

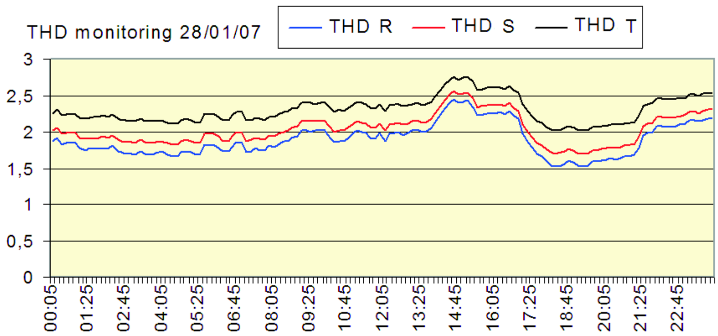


Fig. 5b. Three phase THD voltage monitoring in a day.

RMS voltage and current values have been chosen equal to 230 V and 1.357 A respectively; phase angle has been varied between $-\pi/4$ and $\pi/2$ rad. Active and reactive powers have been measured; the results are shown in Table I. It can be seen that the relative deviation does not exceed 2%. Moreover the results of one day and one-week of three phase THD voltage (see Figs. 5 a and b) and three-phase RMS voltage (see Figs. 6 a and b) monitoring of the electrical network in the Second University of Naples have been reported.

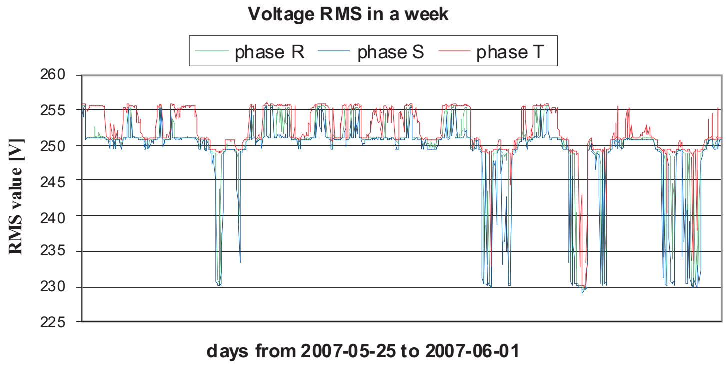


Fig. 6a. Three-phase RMS voltage monitoring in a week.

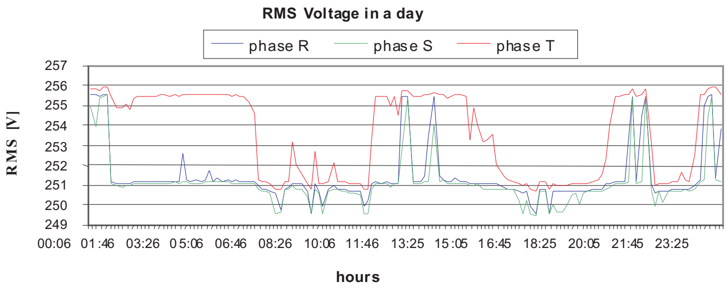
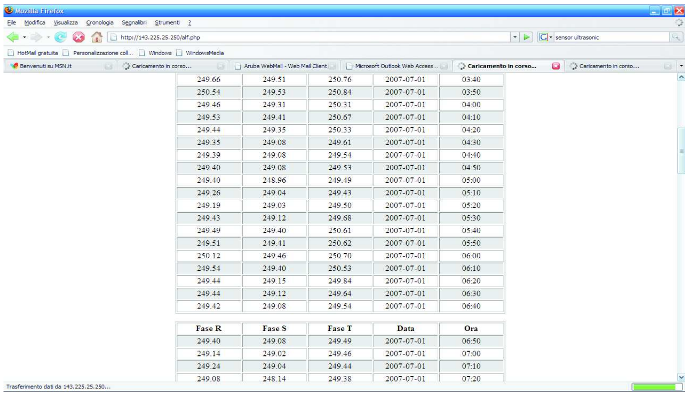


Fig. 6b. Three phase RMS voltage monitoring in a day.

5. PHP CLIENTS

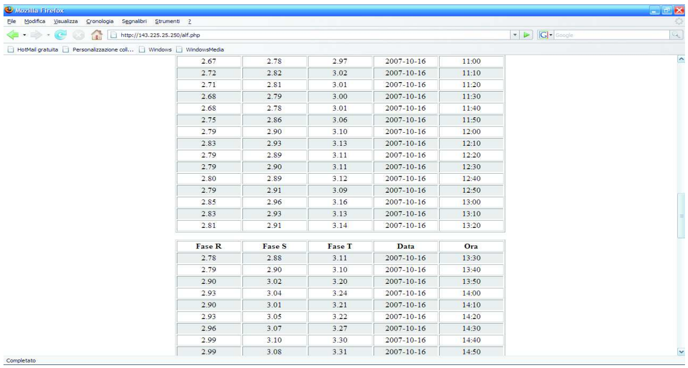
Once the data are acquired and stored, we must publish them; it is possible to use the integrated Web server to run web client to query the database that contains the results. The first client was developed in PHP language and returns the requested data in table format; when calling the client, you see a page that allows the end user to select the desired service. Figures 7 and 8 show the pages of return to requests respectively for RMS voltage values and THD voltage values.

The values are averaged over 10 minutes. In Figure 9 the page of return to requests of dips is shown.



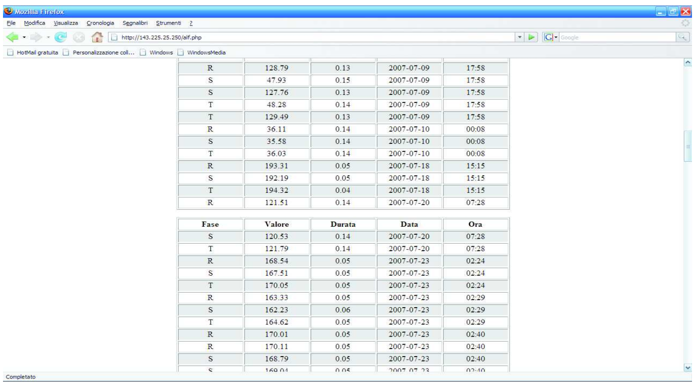
Fase R	Fase S	Fase T	Data	Ora
249.66	249.51	250.76	2007-07-01	03:40
250.54	249.53	250.84	2007-07-01	03:50
249.46	249.31	250.31	2007-07-01	04:00
249.53	249.41	250.67	2007-07-01	04:10
249.44	249.35	250.33	2007-07-01	04:20
249.35	249.08	249.61	2007-07-01	04:30
249.39	249.08	249.54	2007-07-01	04:40
249.40	249.08	249.53	2007-07-01	04:50
249.40	248.96	249.49	2007-07-01	05:00
249.26	249.04	249.43	2007-07-01	05:10
249.19	249.03	249.50	2007-07-01	05:20
249.43	249.12	249.68	2007-07-01	05:30
249.49	249.40	250.61	2007-07-01	05:40
249.51	249.41	250.62	2007-07-01	05:50
250.12	249.46	250.70	2007-07-01	06:00
249.54	249.40	250.53	2007-07-01	06:10
249.44	249.15	249.84	2007-07-01	06:20
249.44	249.12	249.64	2007-07-01	06:30
249.42	249.08	249.54	2007-07-01	06:40
249.40	249.08	249.49	2007-07-01	06:50
249.14	249.02	249.46	2007-07-01	07:00
249.24	249.04	249.44	2007-07-01	07:10
249.08	248.14	249.38	2007-07-01	07:20

Fig.7. Table for request of RMS values in a three-phase line.



Fase R	Fase S	Fase T	Data	Ora
2.67	2.78	2.97	2007-10-16	11:00
2.72	2.82	3.02	2007-10-16	11:10
2.71	2.81	3.01	2007-10-16	11:20
2.68	2.79	3.00	2007-10-16	11:30
2.68	2.78	3.01	2007-10-16	11:40
2.75	2.86	3.06	2007-10-16	11:50
2.79	2.90	3.10	2007-10-16	12:00
2.83	2.93	3.13	2007-10-16	12:10
2.79	2.89	3.11	2007-10-16	12:20
2.79	2.90	3.11	2007-10-16	12:30
2.80	2.89	3.12	2007-10-16	12:40
2.79	2.91	3.09	2007-10-16	12:50
2.85	2.96	3.16	2007-10-16	13:00
2.83	2.93	3.13	2007-10-16	13:10
2.81	2.91	3.14	2007-10-16	13:20
2.78	2.88	3.11	2007-10-16	13:30
2.79	2.90	3.10	2007-10-16	13:40
2.90	3.02	3.20	2007-10-16	13:50
2.93	3.04	3.24	2007-10-16	14:00
2.90	3.01	3.21	2007-10-16	14:10
2.93	3.05	3.22	2007-10-16	14:20
2.96	3.07	3.27	2007-10-16	14:30
2.99	3.10	3.30	2007-10-16	14:40
2.99	3.08	3.31	2007-10-16	14:50

Fig. 8. Table for request of THD values in a three-phase line.



Fase	Valore	Durata	Data	Ora
R	128.79	0.13	2007-07-09	17:58
S	47.93	0.15	2007-07-09	17:58
S	127.76	0.13	2007-07-09	17:58
T	48.28	0.14	2007-07-09	17:58
T	129.49	0.13	2007-07-09	17:58
R	36.11	0.14	2007-07-10	00:08
S	35.58	0.14	2007-07-10	00:08
T	36.03	0.14	2007-07-10	00:08
R	193.31	0.05	2007-07-18	15:15
S	192.19	0.05	2007-07-18	15:15
T	194.32	0.04	2007-07-18	15:15
R	121.51	0.14	2007-07-20	07:28
S	120.53	0.14	2007-07-20	07:28
T	121.79	0.14	2007-07-20	07:28
R	168.54	0.05	2007-07-23	02:24
S	167.51	0.05	2007-07-23	02:24
T	170.05	0.05	2007-07-23	02:24
R	163.33	0.05	2007-07-23	02:29
S	162.23	0.06	2007-07-23	02:29
T	164.62	0.05	2007-07-23	02:29
R	170.01	0.05	2007-07-23	02:40
R	170.11	0.05	2007-07-23	02:40
S	168.79	0.05	2007-07-23	02:40
S	169.04	0.05	2007-07-23	02:40

Fig. 9. Table for request of dip values in a three-phase line.

6. CONCLUSIONS

In this paper the design and implementation of a multi-processor measuring instrument based on DSPs has been discussed. After a detailed prototype description, a part of the analysis algorithm has been reported. Particular attention has been devoted to synchronization problems among all devices that compose the proposed distributed system accounting characteristics of main synchronization standards. The particular metrological application chosen has been the monitoring of RMS values in tree-phase power networks. A proper synchronization protocol has been adopted in order to synchronize to different hardware sections of the sensor performing the measurement.

A measurement station for the characterization of the realized instrument has been built-up and the experimental results are shown; these experimental monitoring results are made during a whole week and are reported also in a one-day graph. The paper has been completed showing some simple PHP clients for the publication of remote results.

REFERENCES

1. Bucci G., Germano A., Landi C.: *The Real-Time Implementation of A Model-Based Measurement Technique on a Multiprocessor Instrument*, IEEE Trans. on I&M, vol. 45, Feb. 1996.
2. Avallone F., De Capua C., Landi C.: *Metrological performance improvement for power measurements on variable speed drives*, Measurement, vol. 21, no. 1–2, pp. 17–24, 1997.
3. Bucci G., Landi C.: *On-line Power Measurement in Non-Sinusoidal Condition By Using A FRLS Algorithm*, Proc. of IMEKO-TC4 '95, Prague (Czech Republic) 1995.
4. Bucci G., Germano A., Landi C.: *Real-time Harmonics Estimation on Power System by means of a Transputer-based Measurement Apparatus*, XIII IMEKO World Congress, Torino (I), Sept.94.
5. Ciancetta F., D'Apice B., Gallo D., Landi C.: *Plug-n-Play Smart Sensor based on Web Service*, IEEE Sensors Journal Special Issue on Intelligent Sensors, May 2007, vol. 7, no. 5, pp. 882–889.
6. D'Apice B., Gallo D., Landi C., Rignano N.: *Distributed Laboratory for Metrological Confirmation of Power Quality Instruments*, IEEE VECIMS 2005 Giardini Naxos , Italy, 18–20 July 2005.
7. Pottie J., Kaiser W. J.: Embedding the internet: *Wireless integrated network sensors*, Communications of the ACM, 43(5), pp. 51–58, May 2000.
8. IEC EN 61000-4-30, 2003, *Testing and measurement techniques – Power quality measurement methods*.
9. IEC Standard EN 61000-4-7, *Testing and measurement techniques – General guide on harmonics and interharmonics measurements and instrumentation, for power supply systems and equipment connected thereto*, 2003-07.
10. Gallo D., Landi C., Rignano N.: *Multifunction Dsp Based Real-Time Power Quality Analyzer*, XVIII IMEKO WORLD CONGRESS Metrology for a Sustainable Development, 2006, Rio de Janeiro, Brazil.
11. Gallo D., Landi C., Rignano N.: *DSP based Instrument for Real-Time PQ Analysis*, ISIE 2007, Vigo (Spain).
12. IEEE P1564™, Draft 6, *Recommended Practice for the Establishment of Voltage Sag Indices*, Transmission and Distribution Committee of the IEEE PES, January 22, 2004.