

# A Multi-DSP Based instrument for Real-Time Energy and PQ Measurements

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**Abstract-** The evaluation of electrical energy flows is at the base of all operations connected to the commercial transactions in 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 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 processor and analog I/O modules, specifically designed to obtain the flexibility and scalability to meet the needs of real-time measurement applications and low cost. After a prototype description, a part of analysis algorithm is reported. The paper is completed by preliminary results of metrological characterization.

## I. Introduction

Electrical energy measurement plays a crucial role not only in the 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 it has been introduced the possibility, for the customers that receive high and medium voltage and for the companies of distribution of the electrical energy, of stipulating contracts for the quality. 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 which the level of quality has not been respected in. This requires the real-time determination of energy flows and correspondent 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 multiply and add. 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 a 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 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 the processor performance. High performance systems are generally based on multi-DSP, to provide enough flexibility and scalability to meet system constraints at relatively low costs. In these systems, each DSP conducts a portion of the signal processing, concurrently to the other ones [1,2]. In the last years new microcontrollers with Harvard architecture are on the market; they allows low cost and moderately high performances.

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 applications. In the designed equipment 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.

## II. Measurement Instrument

The most difficulty for the designer of instrument for real-time applications, is that the DSP overall computing power is not 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 high. For the applications that require frequent short data transfers, the latency time may be a fundamental parameter. This is the case of the processing of new data every clock cycle, as required by recursive measurement algorithms.

### A. Hardware implementation

The measurement system is composed by a multi DSP section, where each single Multiprocessor system is formed by 3 DSP. 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, 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 a pre processing of acquired samples the DSP exchange the data with a microkernel embedded Linux board, through different serial port. This Linux board is based on the ETRAX LX100 MCM processor with 4MB program memory and 16MB data memory. It is useful either as a stand alone device for network applications like micro Web server or as a socket module to integrate in application board. ETRAX LX100 is a 32bit RISC CPU at 100MIPs with on-chip Ethernet interface (10/100 Mb/s) and 2 USB 1.1 port. Moreover it is possible to compile C application, make CGI and Data Base with SQL. In this way, the system is able to mount USB mass storage device where stores SQL date base with measurement results. The Linux board has the task of: i) manages the communication with the different DSP devices, through the serial port; ii) data post processing; iii) manages and stores the data in DB; iv) manages the remote communications as a server; v) publish the results [5].

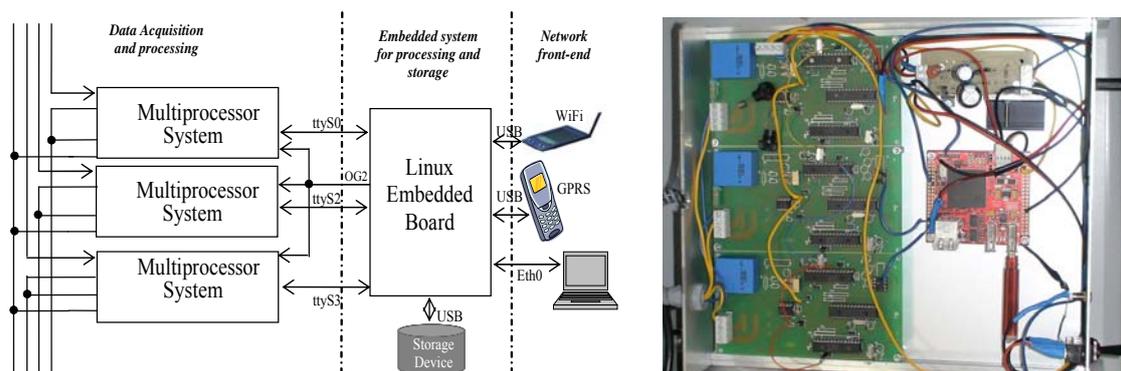


Fig. 1 MultiDSP implemented system

### B. 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 scheduling 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 the maximum control over the hardware with the minimum run-time overhead. If the executed program will repeatedly perform a single sequential set of tasks, as typically occurs on 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 the takes place when both the inputting and the outputting processes are ready: the processes which first becomes ready must wait until the second one is also ready.

The DSP board can perform 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 designer can significantly reduce system development time and costs.

### III. 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:

$$s_n = \sum_{v=0}^{M-1} S(v) e^{j\frac{2\pi}{M}vn} \quad (1)$$

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:

$$\begin{aligned} s_n &= s_n^{(r)} + js_n^{(i)} = \\ &= \sum_{v=0}^{M-1} (S_v^{(r)} \cos \frac{2\pi vm}{M} - S_v^{(i)} \sin \frac{2\pi vm}{M}) + j(S_v^{(i)} \cos \frac{2\pi vm}{M} + S_v^{(r)} \sin \frac{2\pi vm}{M}) \end{aligned} \quad (2)$$

Because of the periodicity of the (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  $s_n^{(r)}$ , is given by the following stochastic difference equations:

$$\begin{cases} x_{n+1} = Fx_n + Gw_n \\ s_n^{(r)} = Hx_n + v_n s_n^{(r)} \end{cases} \quad (3)$$

where  $x_n$  (by order  $2N \times 1$ ) is the state-space vector,  $F$  ( $2N \times 2N$ ) is the system matrix,  $H$  ( $1 \times 2N$ ) 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  $s_n^{(r)}$ , has been obtained by applying FRLS theory [3]. The magnitude  $A_v$  and phase  $\alpha_v$  of the  $v$  order signal harmonic, at each sampling time, is thus given by:

$$A_v = \sqrt{x(2v+1)^2 + x(2v+2)^2} \quad \alpha_v = \tan^{-1} \left( \frac{x(2v+2)}{x(2v+1)} \right) \quad (4)$$

where  $v=0$  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  $V_v$  and currents  $I_v$  content;
- .the voltage and current effective (RMS) values;
- .their crest (ratio of peak to rms) factors;
- .the mean power:

$$P = \sum_{v=0}^N V_v I_v \cos(\Phi_v) \quad (5)$$

where  $\Phi_v$  is the phase angle for sinusoidal excitation of  $v$ th harmonic frequency;  
 .the harmonic active power;  
 .the power factor:

$$\text{p.f.} = \frac{\sum_{v=0}^N V_v I_v \cos(\Phi_v)}{V_{\text{rms}} I_{\text{rms}}} = \frac{\sum_{v=0}^N V_v I_v \cos(\Phi_v)}{\sqrt{\sum_{v=0}^N V_v^2} \sqrt{\sum_{v=0}^N I_v^2}} \quad (6);$$

.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  $f_0$  .

### III. Communications front-end

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 micro-kernel Linux. 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 in your own application board. ETRAX LX100 is a 32bit RISC CPU at 100MIPs with on chip Ethernet interface (10/100 Mb/s) and 2 USB 1.1 port.

The kernel Linux 2.6 version is compiled on board with the 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 USB mass storage device where store SQL data base with measurement results.

#### C. 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.

#### D. Synchronization handshake

During boot time, Fox board synchronizes the starting of acquisition of the three DSP adopting a hand shaking protocol. For implementing this protocol, in addition to serial interfaces a digital output of the fox board (OG2) connected to all the DSP has been used. The adopted hand shaking 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 become low, dsPICs begin acquisition and pre-processing operations.

In order to implement the communication of a flagging event, another hand shaking protocol is implemented. If the event, such as dip, occurs during the monitoring, the second hand shaking protocol is implemented as shown following:

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

A scheme of implemented flagged event protocol is shown in figure 2.

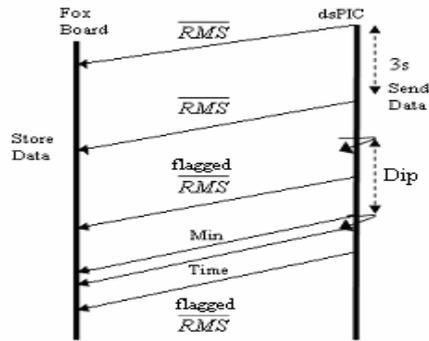


Fig. 2. Flagged event protocol

#### IV. experimental 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 by a signal generator, implemented in CVI environment, that drive a Pacific Power source AMX3120. A reference wattmeter Norma D6100, made by LEM, with an accuracy on 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 IEEE 488 bus. Voltage and current r.m.s. values have been chosen equal to 230 V and 1.357 A; 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 relative deviation doesn't exceed 2%. Moreover, in fig. 2 and 3 the results of one-day and one-week of three phase voltage THD and three phase voltage RMS monitoring of electrical network in Second University of Naples have been reported.

Table I-electrical power test

Phase angle	Active Power (kW)			Reactive Power (kVAR)		
	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

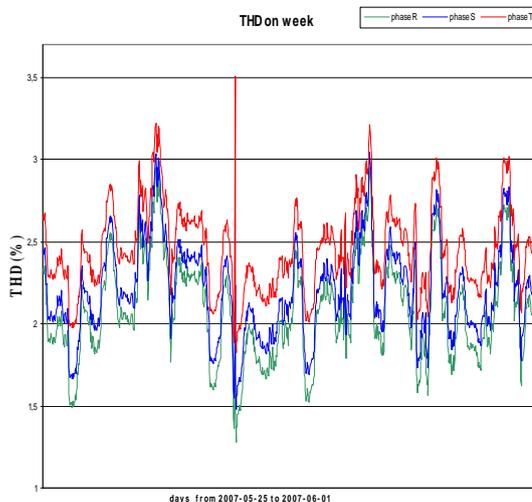


Fig. 3-a Three phase voltage THD monitoring on week

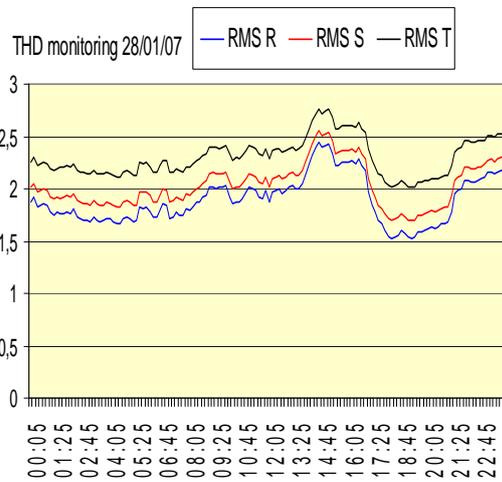


Fig. 3-b Three phase voltage THD monitoring on day

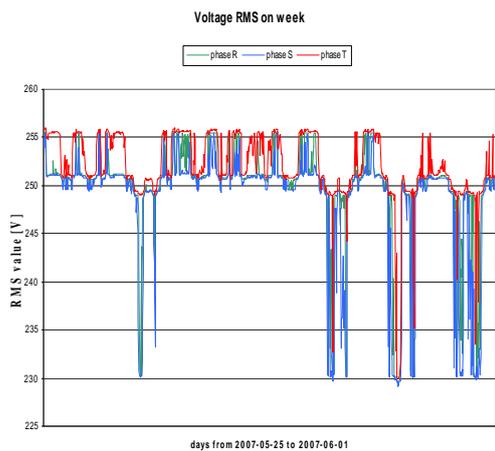


Fig. 4-a Three phase voltage THD monitoring on week

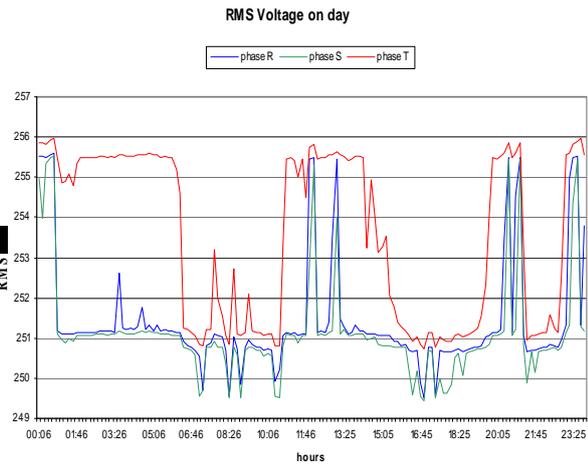


Fig. 4-b Three phase voltage THD monitoring on day

## V. 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 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 three-phase power networks. A proper synchronization protocol has been adopted in order to synchronize to different hardware sections of the sensor performing measurement.

The paper has been completed by preliminary results of metrological characterization, in terms of electrical power measure and RMS value and THD value of three phase network voltage. These monitoring are made on whole week and are reported also in a one day graph. In future, extended experimental results for instrument characterization will be made.

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