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A New Platform for High Accuracy Power Quality Measurements: the Forensic Point of View

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Abstract – **A new platform for Power Quality measurement based on PIC 32 family microcontroller has been realized and tested. The board is able to determine the frequency of the mains implementing the Curve Fitting Algorithm and is able to detect punctual events as short interruptions. The device allows performing high accuracy measurements and is a good candidate as platform to use in civil suit in the subject of Power Quality analysis.**

I.   INTRODUCTION

The relational model established between the production / distribution of electrical energy and the customers is a top-down model in which the apex are the producers and distributors, while, at the bottom, there are the customers[1].

The companies that produce and distribute the good electrical energy are, for historic reasons, monopolistic or ex-monopolistic, and have giant economic dimension. For all the '900, they symbolized the engine of the economic development for all nations, supplying a good able to be converted into goods and services useful for the population. These companies have grown in their own country in a protected system without a true competition which could threaten their existence. This made these societies privileged than the others and made them impervious to criticism, preserving them from any kind of significant legal or commercial actions that could threaten their existence, activity and structure. The only request that was normally done to this company was to carry out the duty with continuity, forgiving possible local inefficiencies or attitudes not much inclined to the current market rules observed in all other commercial sectors.

On the other hand, the customers, clients of supplier/distributor of electric energy company and beneficiary of the good. They present a lot of commercial disadvantages, first of all the trifling dimensions that reduce the bargaining power, but worst thing, they present a deeply cultural gap toward the good electrical energy that detracts their capacity to understand this good. In fact, the man has not biological sensors able to allow the quantification of the electrical energy moreover, to this natural condition, it is possible to add that most of people hasn't a specific technical/scientific culture so that the comprehension of the electrical energy is truly hazy [1-5].

This lack of knowledge is the base of the electrical energy supplier power in the management of the clientele. Therefore, the companies impose their will to customers not satisfying their true exigencies because of their inability to quantify the electrical energy. In this way the user doesn't know what to ask to electrical energy good and he is also not able to form a own conscience in this subject so he is not even stimulated to try information on an argument anyway irksome both for mathematical and practical point of view.

The electrical energy supplier could help to overcome this situation, but it has no will to change the "status quo" because this lack of knowledge and the lack of will to knowledge is the base of present relations between it and the customers.

To back this thesis is sufficient to read the general conditions of the electrical energy supply agreement specifically in the articles related to "Interruption of the supply and supplier responsibility. Responsibility or not of the user". If we read the 7th article of the "General condition of delivery" [6] made by ENEL Energy SpA, the most important Italian electrical energy producer, to the paragraphs 2, 3 and 4, we can find the following sentences:

- Paragraph 2: "….the interruptions or the limitations of the supply, due to accidental causes, for reasons beyond one's control or anyway not attributable to the Supplier, will not produce indemnity or refund nor they can be reasons to the cancellation of the contract."

- Paragraph 3: "**In particular, the Supplier <u>is not responsible</u> of the damages consequent on technical problems related to the delivery of the electrical energy as, for example, amplitude or frequency voltage variations, waveform variations, interruptions of electrical energy supply continuity, micro-interruptions, voltage dips and, in general, anomalies consequent on the management of the electrical energy plants of the User.**"

- Paragraph 4: "**The User is obliged to release the Supplier for each controversy or payment of burdens or damages that might arise to it during the execution of the services presents on the Contract and that derive by facts or behaviours due to the Client**."

The interpretation of these paragraphs is simple: if the user does not know the good "electrical energy" and the related world, how can he knows which are the accidental or the beyond one's control reasons that can interrupt the supply? How can he knows which are the voltage dips, the waveform or the frequency etc.? How can he knows if these characteristics are changed? How can he knows what these changes can produce on electric and electronic domestic devices? Moreover, more important, how can he knows if these variations are produced by oneself or not?

It is obvious that the **absence of electrical energy Measurements** makes everything absolutely aleatory.

In this situation, the possibility to vindicate one's right is impossible [1-5].

Based on the epochal changes happened in the world of energy in the last few years, this consolidated relational model has been called into question. In fact, the introduction of the Free Market in the energy world has had, as consequence, the creation of a "super partes" external qualified non-profit-making national agency The Electrical Energy and Gas Authority founded to protect the customer's interests in Italy.

With the "Integrated text for the regulation of the quality of the distribution, measurements and selling services of the electrical energy"[7] the Authority performed a remarkable work under an economic/legal point of view. In fact, it simplified and clarified the writing of producer/user contract and electricity bill, so permitting an easy reading of these and of commercial offer coming from different producers. It fixed certain rules for quality commercial levels, establishing when and how of actions to adopt for the management of reclaims and estimates or time for execution work etc..

Under a technical point of view, the concept of quality is used weaker. In fact, for the low voltage (BT) customers, the Authority establishes precise rules only for the voltage dips, while for the other parameters defined to the CEI EN 50160 [8,9] norms, it will put off to fix a own regulations in the future. This last and its updating CEI 110-22 are the norms that specify the voltage characteristics of electricity supplied by public distribution networks, and the Authority establishes that the instruments to make the measurements have to respect the CEI IEC 61000-4-7 [10] and CEI IEC 61000-4-30 [11].

Formally, the Authority gives the possibility to stipulate a producer/customer contract based on the Quality, agreement that can be stipulated after an observation period of one year of the electrical energy. Practically, the technical problems make extremely hard

and expensive the development of specific instrumentation able to satisfy the Authority needs. For these reasons, at the moment, this kind of agreement are extremely hard to prepare.

In the market, there are many instruments that measure the Power Quality but they have several order of problems as, for e.g.:

1) often, the analogical interfaces, starting form sensors, are not correctly thought for PQ needs. For e.g., the use of ferromagnetic core sensors with pass band too small doesn't allow to correctly measure the harmonic and interharmonic content of the input signal;
2) usually, the instruments, cause their little memory deep, are not designed to obtain automatic measurements for long time;
3) multiple channels acquisition cards often use a multiplexed management for the input channels, this produces an incorrect registration of the electric phases under analysis[2,5,12];
4) the acquisition trigger is not connected to a metrological time reference making the metrological approach toward the measurements fruitless, or, where it is verified, the multiplexing is managed by a local clock that has a poor time accuracy [2,5,12];
5) instruments designed for automatic stand alone measurements have not yet a high reliability[2,12];
6) high accuracy instrumentation is expensive[13,14];

These lasts four problems have been directly faced on instrument realized by ourselves and partially solved with a complex uncertainty determination (problem 3) [3] or with suitable recovery remote control system (problem 5)[12].

In this work, we show a new platform for PQ measurements based on PIC 32 Microchip microcontrollers family able to extract the grid frequency and able to check punctual events as short interruptions.

Combining new performance hardware and a firmware based on Curve Fitting Algorithm (CFA)[1-5], the device wants to face and partially solve the above list, proposing itself as inexpensive but able to satisfy high accuracy requests. In this way the proposed system is a serious candidate to became a platform to perform measurements for the PQ evaluation and so to became an instrument usable to support the preparation of an agreement which consider also the concept of quality. The proposed system can also be used as part of a black box, with the saving of the data streaming, the date and time indication of possible anomalies, if any, usable in forensic context to evaluate if the agreement has been respected.

The paper is organized as follows: in paragraph II, we show the hardware of the platform, paragraph III describes the firmware also recalling the CFA algorithm, and then some tests will be shown. Conclusions and perspectives will be described at the end.

II. HARDWARE

As Fig. 1 shows, the block scheme of the platform is composed by an input stage, the analog to digital section, the microcontroller and a control logic for the overall management of the system.

The entities, input of the board, are voltages and currents. Specifically four voltages (Vr, Vs, Vt and Vn), with a nominal value of 230 Vrms between a phase and the neutral and 4 currents (Ir, Is, It, In) acquired with Rogowski coil current sensors. The input stage is composed of eight operational amplifiers in voltage follower configuration. The inputs are connected to a terminal block and the outputs are connected to the ADC. There are precision resistive dividers (accuracy of 0.1 %) that reduce the amplitude of the grid voltage of 1/100 were not included in the main board, but on a secondary one. Even the Rogowski coils have not been included in the card, so only the 4 voltage channels were used. The Input stage conceived in this combined with the CFA algorithm ensures high accuracy measurements.
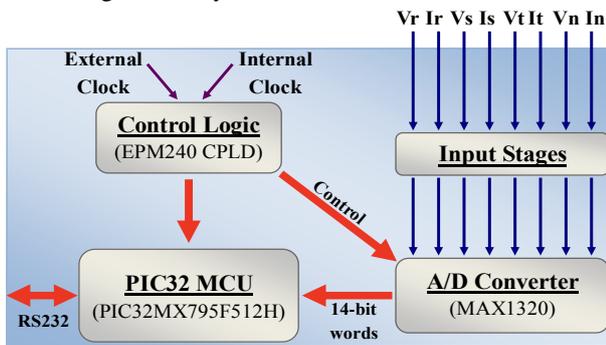

Fig. 1. Block scheme of the platform.

The MAX1320 is an analog to digital SAR type converter produced by Maxim Integrated. It is a 14-bit ADC with 2, 4 or 8 selectable input channels. A special feature of this ADC is to be able to perform a simultaneous sampling on all its channels (preserving the relative phase information). In this work, 4-channel configuration has been used.

For the control logic has been selected the CPLD EPM240T100C5 from MAX II, family of Altera. The CPLD is programmed or to determine the grid frequency or to detect punctual events. In the first case, CPLD tasks are:
- starts the ADC conversion with a specific sampling frequency (25 kHz);
- counts the number of acquisitions and stops the process when the requested number of them is achieved (1500, corresponding to 3 periods of 50 Hz mains fundamental);
- generates a reference signal towards the PIC, for the transfer of data from the ADC buffer;
- restart the "burst of 1500 conversions" every minute.

For the punctual events, it must continually generate the clock to start the A/D conversion at a frequency of 204.8 kHz greater than the previous case because the system has to detect events extremely quick. The conversion is done in free-running mode while the PIC "listen" the end conversion signal from the ADC to acquire data. The PIC32 (or microcontroller unit MCU) is the heart of the project. For the microcontroller, it has been chosen the PIC32MX795F512H from Microchip Technology Inc. Among its features, we have: a 32-bit MIPS core with a working frequency of 80 MHz, a RAM of 128 kB and 512 kB of FLASH memory. The MCU acquires samples from the ADC, performs the algorithm for monitoring or for the detection of events, and then transfers the data calculated or the entire record of the acquired values to the PC via a serial connection.

The cards are designed to work with an external metrological clock with high accuracy (10^{-14}) provided by the Italian Institute for Metrological Research-INRIM of Turin with a frequency of 2048 kHz. In the absence of this external clock is provided the generation of an internal clock on the card, always at the frequency of 2048 kHz.

The overall hardware platform has been divided in three interconnected PCBs: an underlying motherboard, a card specific for the ADC and one for the PIC and the circuitry required for its operation. The developed board is shown in Fig. 2.
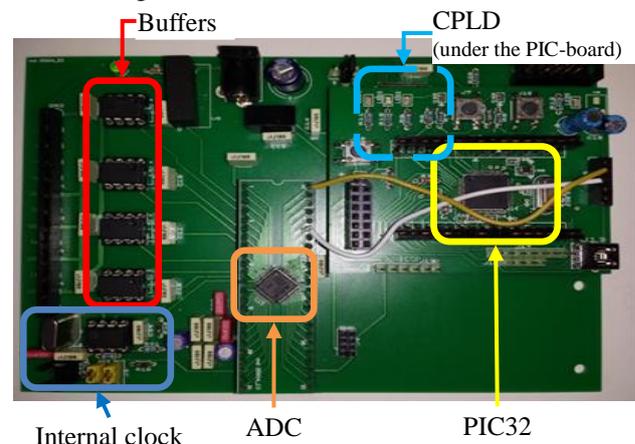

Fig. 2. Picture of the developed board.

The various supply voltages on the card is obtained by using DC/DC switching converters. The DC/DC provides a dual voltage of ± 5 V at the input stage and a voltage of 3.3 V for all the digital part. These converters can be powered from a +5 V classic power supply or from the mini-USB socket on the PIC-board.

To the left of Fig. 2 it is possible to see an empty slot. This is the predisposition of the board for the use of a GPS module to associate a "time-stamp" to the acquired samples, the calculated data and the detected events.

The development environment used to program the microcontroller is officially provided by Microchip (MPLAB - X v1.95).

III. FIRMWARE

There are two versions of the firmware to be inserted within the MCU, one for quality monitoring and one for events-detection.

A. Frequency determination

The main feature of this version is to receive 1500 acquisitions every minute. Each acquisition has 4 samples (Vr, Vs, Vt, Vn) of 14-bit each one. The four values are simultaneously sampled at a frequency of 25 kHz (RAM occupied by the record of samples: 1500 * 4 * 2 bytes). Collected all 6000 values, the microcontroller executes the algorithm to extract the main frequency and all harmonics, and then sends the computed data to the PC via a serial connection. When the system starts, the MCU configures the registers and the ADC for the 4-channel operation. It expects to receive 6000 samples from 1500 acquisitions. Once received all samples they are stored in an array, and then the algorithm for estimating the frequency and eventually for the determination of harmonics is applied.

To measure the real pulsation ω of the mains signal it has been used the Curve Fitting Algorithm (CFA) [1-5].

This algorithm has a complexity similar to Fourier analysis, but a strongly reduced computing load and allows extracting the frequency with a higher accuracy. Considering the recursive relations:

$$C_i(\omega,T) = \int_0^T Y(t)\, t^i \cos(\omega\, t) dt \quad ; i = 0, 1, \ldots \quad (1')$$

$$S_i(\omega,T) = \int_0^T Y(t)\, t^i \sin(\omega\, t)\, dt \quad ; i = 0, 1, \ldots \quad (1'')$$

The used version of the CFA algorithm permits to evaluate the $\delta\omega$ difference from the ideal grid pulsation (50 Hz), solving a polynomial equation, avoiding recursion:

$$\sum_{i=0}^{g} a_i\, \delta\omega^i = 0 \qquad (2)$$

where a_i coefficients can be calculated as

$$a_i = \left(\frac{2\omega}{i!} \frac{\partial^i Den}{\partial \omega^i} + \frac{2}{(i-1)!} \frac{\partial^{i-1} Den}{\partial \omega^{i-1}} - \frac{1}{i!} \frac{\partial^i Num}{\partial \omega^i} \right)\Bigg|_{\omega=\Omega} \quad (3)$$

Num and Den are defined as:

$$Num = [C_0^2(\omega,T) + S_0^2(\omega,T)] \qquad (4)$$
$$Den = [C_1(\omega,T)S_0(\omega,T) - S_1(\omega,T)C_0(\omega,T)] \qquad (5)$$

The frequency measurement has been realized on the tri-phase direct sequence Vp obtained by the Fortescue decomposition made using the transformation:

$$\begin{bmatrix} V_z \\ V_p \\ V_n \end{bmatrix} = \frac{1}{3} \begin{bmatrix} 1 & 1 & 1 \\ 1 & \alpha & \alpha^2 \\ 1 & \alpha^2 & \alpha \end{bmatrix} \begin{bmatrix} V_R \\ V_S \\ V_T \end{bmatrix} \qquad (6)$$

with

$$\alpha = -\frac{1}{2} + j\sqrt{3} \qquad (7)$$

Normally, the zero sequence Vz and the negative sequence Vn are null. Sequence component analysis plays an essential role in analysis of power system faults and in explaining some power system phenomena.

The measurement method uses the integration of the noise in each measurement points: this strongly reduces the mains noise.

Estimated the grid frequency, modulus and phase of the harmonics, up to the 40th, can be also calculated.

Finally, the computed data are sent to the PC via a RS232 serial communication and the PIC gets back waiting for the next acquisition of 6000 samples. Fig. 3 shows the flowchart of the frequency determination firmware
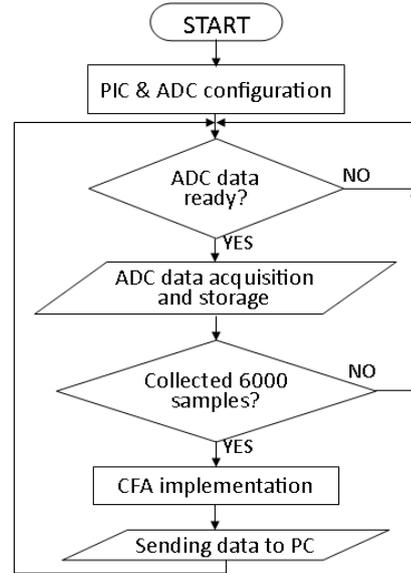

Fig. 3. Flowchart of frequency determination firmware.

B. Detection of transient events

In this case (see Fig. 4), the ADC continuously samples at 204.8 kHz and (consequently) a fast and optimized algorithm for real-time event-detection is implemented.
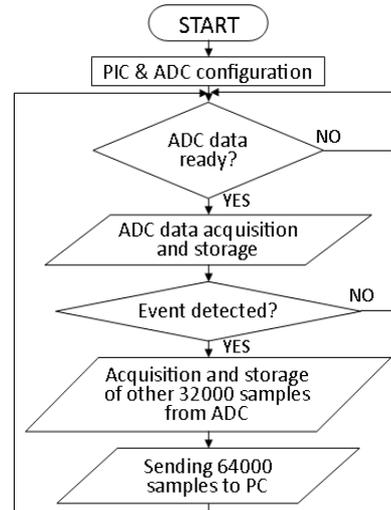

Fig. 4. Flowchart of event-detection firmware.

In fact, the event must be detected between a sampling and the next one.

At the startup, the PIC32 initializes registers and configures the ADC for the 4-channel operation. When they are ready, it acquires the samples of the 4 voltages (Vr, Vs, Vt, Vn) and stores them in an array. Then the sum of the three phases voltages respect to the neutral is calculated:

$$SUM = (r - n) + (s - n) + (t - n) = r + s + t - 3n \quad (8)$$

The difference between the sum just calculated and the previous one is also evaluated. The comparison between this difference and a threshold value determines the existence of the event.

$$|Sum[n] - Sum[n-1]| > threshold \rightarrow anomaly \quad (9)$$

Each obtained value is of 14-bit (occupies 2 bytes of memory), each acquisition provides 4 values (Vr, Vs, Vt, Vn), therefore 8 bytes for acquisition. The PIC32 selected has a RAM of 128 kB (131072 bytes), freeing some bytes for program variables, you can store up to 16000 consecutive acquisitions.

$$Size\ of\ samples\ array: 2*4*16000 = 128000\ byte \quad (10)$$

Once an event is detected, the acquisitions continue until the PIC memory is full and the "anomalous" samples are in the middle of the record. Then, the PIC sends to the PC the whole array of samples and, later, continues with acquisitions.

IV. TESTS AND MEASUREMENTS

Fig. 5 shows the laboratory measurement bench where the tri-phase is connected to the yellow card where are placed the voltage dividers, this is connected to the board and the results are then sent to the PC.
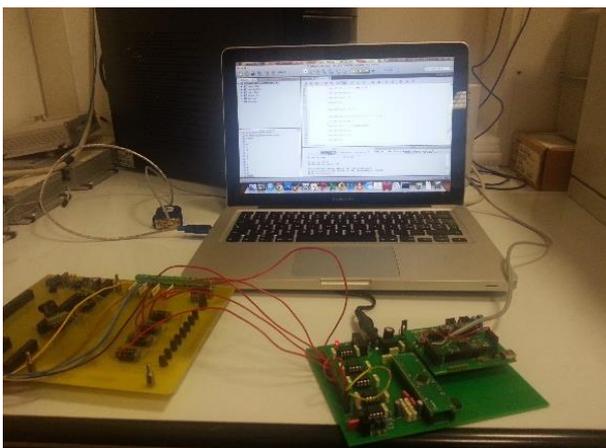

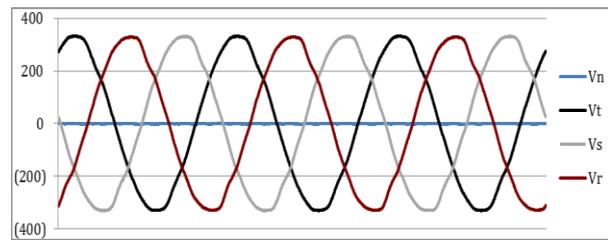*Fig.5 Measurement test bench.*

Fig. 6 shows the acquired data.

Fig.6 Acquired data from the laboratory tri-phase mains.

Fig. 7 shows another kind of test: a 49.15 Hz triangular signal generated by a Yokogawa function generator has been sent to a channel of the board.

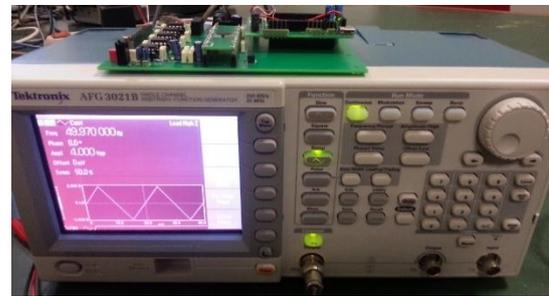The board correctly calculates the fundamental and its harmonics.

Fig.7 Triangular signal sent to the board.

V. THE FORENSIC APPLICATION

The system shown has been conceived to automatically acquire PQ information of the network under control. The device has been also conceived to send to a remote server these data and there stored in encoded form. The database so realized could help in case of lawsuit helping the court expert to signal which PQ parameters have exceeded the preset threshold by the norms.

VI. CONCLUSIONS AND PERSPECTIVES

A new platform for Power Quality measurement has been realized and tested. The board, based on PIC 32 family microcontroller is able to determine the frequency of the mains implementing the Curve Fitting Algorithm, and is able to detect punctual events as suggested by the norm. The device is particularly inexpensive and allows performing high accuracy measurements. The device is now under further functional tests. The next steps will be the connection of the device directly to internet to provide measurements in a remote control server, and the implementation of other algorithms to find other PQ parameters. This last section will allow to use the proposed system as a part of a black box security system, with the saving, in encoded form, of the data streaming, the date and time indication of possible anomalies, if any, easily usable in forensic context.

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