An Electric Energy Quality Meter Using Hardware Reconfigurable Computing

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Abstract

The use of electronic loads in production processes has been increased lately in the industries, aiming at improving automation and products quality. At the same time, operational costs are reducing, including the cost of electric energy. Together with these advantages many problems appear, such as electromagnetic interferences and harmonics, justifying the insertion of quality and amount of electric energy meters (EEQ meter) for evaluations and analyses for both, consumers and companies. This work describes and analyses several issues in the implementation of a EEQ meter, emphasizing the functional block implementation using hardware reconfigurable computation. The advantages of this approach, such as execution time and parallelism, are explored in this paper.

1 Introduction

The widespread use of automation in industry has lead to remarkable increment in production with growing levels of quality, besides significant reduction of operational costs. Amongst these industrial costs, the electrical energy is one of the most important. In the last decades, the use of electronic loads has become popular. In this kind of load, current and voltage are not proportional (that is, the load is nonlinear), in such a way that disturbances are generated in the electric network. These disturbances, depending on their magnitude, can affect the performance of the electric network as a whole, and the behavior of the loads connected to it [6]. Consequently, there will be a significant influence on the Electric Energy Quality (EEQ).

The commonest signs of the presence of harmonics in the electric line are: excessive heating of generators, motors and transformers with load below the nominal; unexpected triggering of protection devices normal current levels; unexpected resonance or vibration of mechanical parts; relevant voltage difference between neutral and ground wires; overheating or high circulating current in the neutral wire.

Usually, current works about harmonics are focused on measurements and analysis of single customers or specific points in the electric power distribution network [11]. In principle, measurements in individual customers connected to the secondary distribution network are expensive and not useful. However, very few is known about the behavior of the harmonics in customers of the secondary network. Consequently, it would be interesting to monitor the EEQ locally, exactly in the point the energy is delivered to customer, so as to identify possible sources of disturbances in the network.

The project of an instrument for measuring EEQ can be seen from the point of view of an embedded system, with specific processing and data storage characteristics. In recent years, we have witnessed a pronounced growth of the hardware and software technologies for embedded systems, with many technological options arising every year. Therefore, the use of open and reconfigurable structures becomes attractive, especially due to its robustness and flexibility for easy adaptation to different project requirements. Such characteristics can be constraints in the project of an embedded system, particularly for an EEQ meter. Reconfigurable computing (that is, systems based on reconfigurable hardware) is a technology that presents suitable features for this kind of project. Reconfigurable devices have, among other advantages, low power consumption and high speed processing, besides easy programming, flexibility (adaptability to different project requirements), and modular operation [3][8].

This work describes the project of an electric energy quality meter (EEQ meter) using reconfigurable hardware. This device is primarily designed for measurement and analysis of parameters of the electric network in specific customers of the secondary distribution network. It is also meant to substitute the current customer energy meter, in such a way to perform a distributed processing of the electric parameters of the electric network.

This work is in accordance with the recent changes in the regulations of the Brazilian government regarding to the charges and penalties to the utility companies, due to the presence of harmonics in the distribution network [2]. Several issues justify the development of such EEQ meter:

- Demand for low-cost, intelligent meters, from both utility companies and customers.

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- Academic and governmental interest for the EEQ in the Brazilian electric system, in all categories of customers.
- Possibility of integrating an EEQ meter in a domotic system, so as to optimize the energy use in a residence of small enterprise.
- Possibility of applying new embedded systems' technologies in a real-world problem.

The proposed EEQ meter can be configured to work with different profiles, in such a way to be adapted to different companies and customers. Such configuration can be done locally or remotely, and several measurement parameters can be adjusted, such as time between measurements and computations, upper and lower bounds for electrical measurements, number of phases under analysis and IP (Internet Protocol) address. There are some restrictive issues in the implementation of an EEQ meter: processing power and data storage. By using reconfigurable logic it is possible to exploit real parallelism, and so, one can process data more efficiently, achieving real-time performance even for a large amount of data. Also, such implementation can afford for a large amount of local data storage, regarding to the relevant events detected in the network. The processing power can be achieved by developing independent and specific modules in a FPGA (Field Programmable Gate Array) device, such as FFT (Fast Fourier Transform), form-factor, harmonic distortion, average and RMS, etc.

2 Electric Energy Quality - EEQ

The EEQ can be defined as the relative absence of relevant disturbances in the network and, particularly, the absence of shortages, voltage floating, outbreaks or harmonics in the point of power delivery [4]. A given customer can be subject to EEQ problems depending on: the quality of the primary energy generated and distributed by the utility company, the quantity and type of the loads in the nearby network, the sensitivity of the customer's devices to the several electric disturbances. The main electromagnetic phenomena associated to EEQ can be grouped as follows [7]:

- Transient voltage disturbances;
- Instantaneous voltage disturbances;
- Instantaneous frequency disturbances;
- Total harmonic distortion, voltage floating, phase unbalance;
- Noise and electromagnetic interference.

Equations (1) and (2) quantify harmonic distortions, respectively, Individual Harmonic Distortion (IHD) and Total Harmonic Distortion (THD), where h_i are the i-th harmonic:

$$IHD = \frac{h_i}{h_1} \times 100\% \tag{1}$$

$$THD = \frac{\sqrt{h_2^2 + h_3^2 + h_4^2 + h_5^2 + \ldots + h_n^2}}{h_1} \times 100\% \tag{2}$$

In Brazil, current legislation does not fix specific limits for the harmonic distortions in electric networks. Therefore, this work is based on the IEC 610000-3-2 and IEEE P1159.3/D9 standards that specify limits for THD. These standards are complimentary: the IEC standard establishes limits per equipment, whereas the IEEE norm focuses the limits in the point of electric energy delivery [7]

2.1 Power Factor in the Presence of Harmonics

Figure 1 presents the voltage and current waveforms in a non-linear load. It can be observed the nonlinear characteristic of the load, since the current is not proportional to the voltage (sinusoidal).

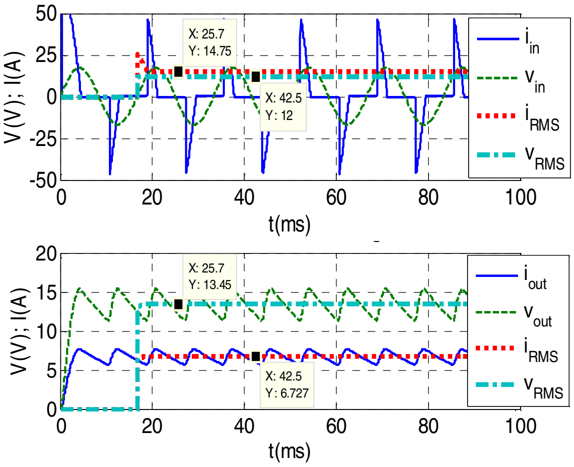

Figure 1 – Voltage and current waveforms in a non-linear load: (top) inputs, (down) outputs.

Figure 2 shows instantaneous power (Watt), RMS power (Volt-Ampere) and average power (Watt), defined, respectively, by equations (3), (4) e (5). In Figure 2, although the instantaneous power is always positive, it can be observed that the average power is smaller than the RMS power, characterizing a power factor smaller than the unity (0.57, in this case). It can be concluded that the origin of the lower power factor is the distortion of the current waveform introduced by a nonlinear load (voltage source).

$$p(t) = v(t) \cdot i(t) \tag{3}$$

$$P_{RMS} = V_{RMS} \cdot I_{RMS} \tag{4}$$

$$P_{average} = \frac{1}{T} \int_{t_0}^{t_0+T} p(t)\, dt \tag{5}$$

By using the concept of power factor (*PF*) and the Fourier series, we can obtain the distortion factor *DistF* (equation (6)) and de true power factor (equation 7):

$$DistF = \frac{1}{1 + DHT^2} \qquad (6)$$

$$PF_{true} = DistF \times \cos\theta \qquad (7)$$

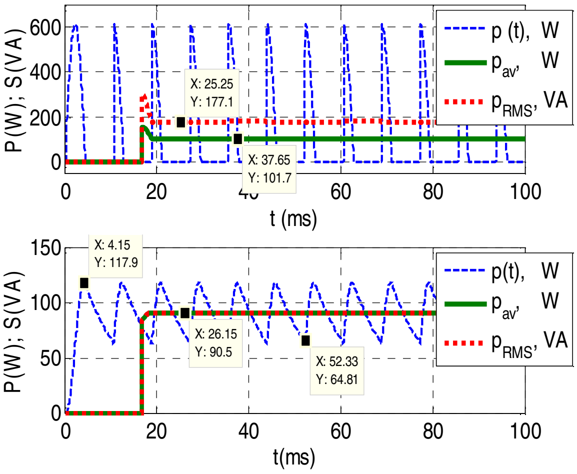

Figure 2 – Instantaneous power, average power and RMS power in a non-linear load: (top) inputs, (down) outputs.

2.2 Hardware Reconfigurable Logic

The synthesis of the logical circuits in PLD is made through CAD (Computer Aid Design) systems, allowing the use of different project interfaces. Examples of interfaces languages used are: graphical (through schematic), VHDL (VHSIC Hardware Description Language) and AHDL (Altera Hardware Description Language). The language VHDL is the standard language of IEEE [3] for hardware description, which provides an integrated frame of development making possible project, simulation, test and documentation of digital circuits. The objective of the reconfigurable architecture concept is to enable an easy and quick adaptation of a project to technological evolutions, for a better portability and interchange ability of the final system. Through the division of the structure in small functional blocks, with very specific dedicated interfaces, the modularisation of the project becomes efficient. This allows first the best specification of the development tasks for a multidisciplinary team of people, then the adaptation of a particular block to a new technological evolution. Some advantages of the project methodology based on reconfigurable logic are [3][9]:

- Parallel Operation, not obeying Von Newmann's model. This is the most advantageous characteristic in relation to the microprocessors and it allows the real time analysis of processed signals.
- Possibility of modular and hierarchical development of a project;
- Time decrease of project, corrections or still of new versions integration, allowing top-down and bottom-up project methodologies;

- Several development interfaces, based on graphic languages (schematic) or in hardware description languages (VHDL, AHDL) are available;
- Possibility of use of tested functions (IP-CORE), reducing the project time in functions of high complexity.

An additional motivation for the use of reconfigurable logic in the implementation of the proposed modules is to growing readiness of devices of great acting capacity. For instance, some more recent FPGAs present characteristics as: great number of pins of I/O (more than 700 pins), impedance controlled and dedicated lines for operation in differential mode, special internal modules: multipliers, PWM (Pulse Width Modulation), dedicated registers for high performance operations, besides a great high-speed RAM storage capacity (close to 2 Mbits). Such devices operate with up to 5 million of logical cells, allowing the implementation of complete processors.

3 The Electric Energy Quality Meter

The proposed instrument is based on a hierarchical architecture represented in the block diagram of Figure 3, representing software or hardware implementations, explained below. Such architecture is organized in several independent blocks, associated to interfaces with sensors and actuators, communication, and memory storage. If further functionalities are required, new blocks can be easily developed and incorporated to the project, allowing a specific configuration for each different requirement.

The proposed meter is part of a decentralized and distributed EEQ system. Therefore, the project is a function of three main constraints: bulk memory size, real-time processing, and data transmission/reception management. Particularly, considering the nature and complexity of the implemented algorithms, memory capacity and processing speed are crucial.

The acquisition module is responsible for sampling electric signals at a rate up to 200,000 samples/sec, with 16 bits resolution. It is worthy to remark that most commercial EEQ instruments use 128 samples/cycle (7680 samples/sec), and few of them can reach up to 1024 samples/cycle (61,440 samples/sec). Considering that some transients can require sampling periods around 1 ns, this instrument is able to capture transients that cannot be detected by others.

The EEQ analysis modules are implemented in reconfigurable logic and are the main focus of this work. Basically, using single-phase voltage and current samples, parameters regarding the EEQ in the delivery point are computed.

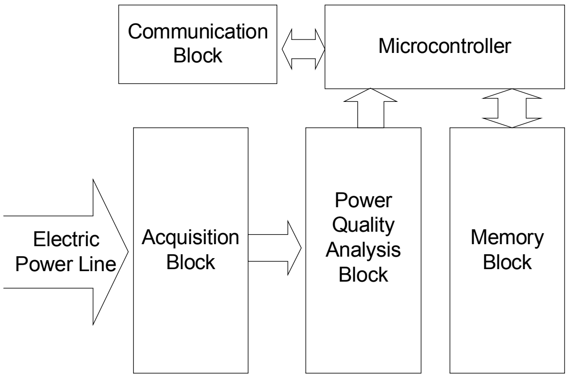

Figure 3 – Simplified block diagram of the EEQ meter.

The communication module is responsible by the periodic transmission of reports, as well as the reception of control parameters and meter configurations.

A reconfigurable hardware-based microcontroller is responsible for managing the information flow and the communications. The architecture of the microcontroller can be specifically projected for this meter, or a well-known architecture can be used (such as MCS51 or ARM).

The non-volatile memory is of fundamental importance so as to meet the project requirements and it is where all the information regarding EEQ of the network are stored.

3.1 Functional Blocks

Figure 5 shows a functional block diagram of the proposed meter. Thanks to parallel processing of such functions, the EEQ parameters can be computed in real-time. Consequently, the amount of data effectively stored (and later, transmitted) is minimized. In this figure the notation adopted is:

- EDB – Input Data Base;
- GS – Group Storage;
- FFT_GS – FFT Group Storage (60 FFTs);
- NT_Dist – Distortion Grade,
- NT_Freq – Frequency Grade;
- CS – Cycle Storage;
- Vrms – RMS Voltage;
- NT_Vrms – RMS Voltage Grade;
- TA – Transient Analysis;
- BC – Bad Cycle Counter;
- NT_T – Transient Grade;
- THD – Total Harmonic Distortion;
- NT – Cycles' Group Grade.

In triphasic measurements, the same procedure for phases-neutral and neutral-ground voltage, line and neutral current is adopted for the computation. It is shown in Figure 5 that all voltages and currents' FFTs are computed at each cycle and at each group of cycles.

The reason for computing the FFT each cycle is mainly to calculate de THD. If THD is larger than 5% then we have a disturbance in the waveform. The next block will analyze if that distortion is a transient or a steady state problem. If it is a transient, a grade will be computed for it. Otherwise, the problem will be considered as a steady state problem. Also, once the FFT is obtained, other important information can be derived, such as the RMS values for voltages and currents.

For distinguishing between transients and harmonics, we use the accumulator BC (Bad Cycle Counter). If a distortion occurs successively for more than a given number of predefined cycles, it is considered as a harmonic distortion, and the previous information computed for transients are discarded.

Analysis for group of cycles is the most popular kind of analyses where we can find harmonic/interharmonic and power frequency variations problems also using the FFT algorithm. Also here, once obtained the FFT, the power factor, the displacement factor and the distortion factor can be computed.

The final grade of the group is the minimum grade of transients, RMS values, harmonic/interharmonic and frequency. The grade of a period (a day, a month) is the average of these groups' grades.

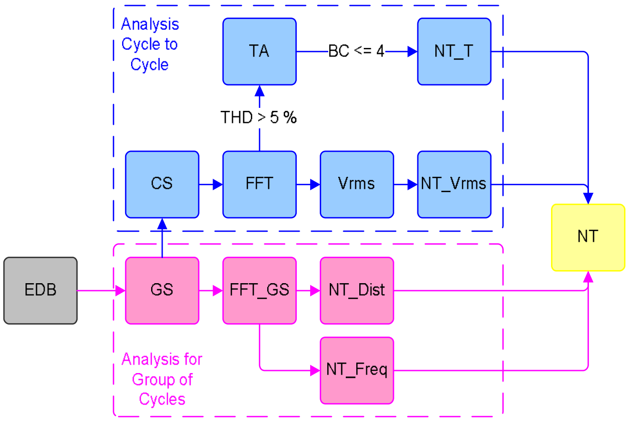

Figure 5 – Simplified functional block diagram of the EEQ meter.

4 Implementation and Results

As mentioned before, we emphasize the use of reconfigurable computing in this project. In this section we show part of this implementation: specific functions of the analysis module of the EEQ meter. It should be noted that several other modules were also implemented in a FPGA: FFT, transient detection, RMS and average values and RMS power.

4.1 Transients

In the transients' analysis, we use the FFT of a single cycle, as shown in Figure 6. In Table 1, the corresponding disturbance analysis report only to the transients in is shown. This analysis can be useful for the diagnosis of failures in the electric system. According to the IEEE standard [7], the minimum number of samples per cycle for this kind of data logging is 128.

Cycle	24	25	26	27
THD_V	0.17917	0.00483	0	0
Note_V	2.8	9.7	10.0	10.0

Table 1 – THD indices for the 24th to the 27th cycles.

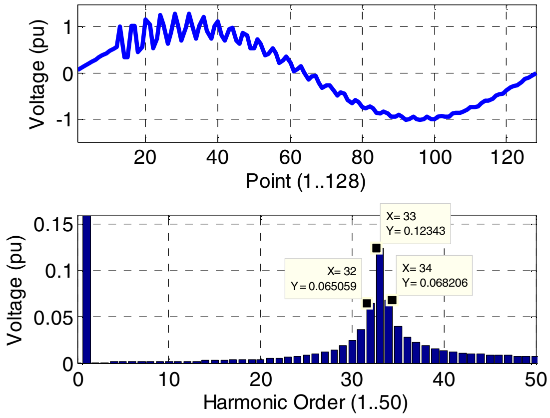

Figure 6 – Example of voltage disturbance.

4.2 RMS Voltage and Current

The RMS values for voltage and current are important output data from the EEQ meter. Such measurements are computed in each cycle, allowing over and under-voltage problems to be recorded, as well as voltage and current unbalances. Figure 8 shows an example of the implementation in graphic language of the RMS function. This module is presented here in graphic language only for didactic purposes, since most of the implementation was done using the VHDL (VHSIC Hardware Description Language) language.

The RMS module works in real-time, computing continuously the RMS value of a window of samples (voltage or current). This module performs a number of mathematical operations, including sum, multiplication, division and square root, with internal resolution of 32 bits. These operations are done between each voltage or current sample. This module can operate with clock frequencies up to 5 MHz. This frequency allows a sampling rate up to 200,000 samples/sec. This fact shows up the advantages of using hardware reconfigurable devices for complex mathematical operations. For the sake of comparison, the execution of only two instructions of a RISC processor (with 10 MHz clock) would consume the same time, and a sequential embedded microcontroller would take even more time.

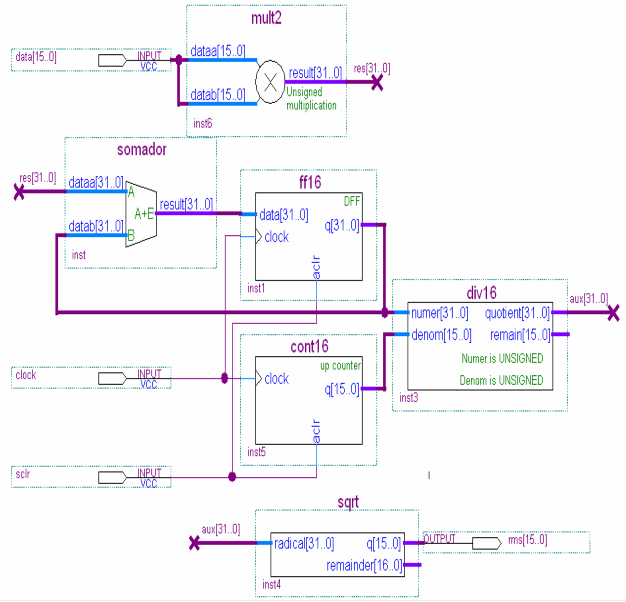

Figure 8 – Example of the implementation of the RMS function in graphic language.

Another important aspect considered is the parallel operation of the logical blocks implemented. It is possible to run up to 6 parallel RMS blocks (for each voltage and current samples of a three phase system). Other before mentioned functions also run in parallel: the FFT, for instance, is also computed independently and in parallel for each phase.

4.3 Harmonics

Figure 9 shows how harmonics can occur along time. The system can be configured to analyze and report the relative evolution of the first 50 harmonics. These data, followed by the corresponding absolute values, can be used as relevant information in the analysis of damages or equipment malfunctioning.

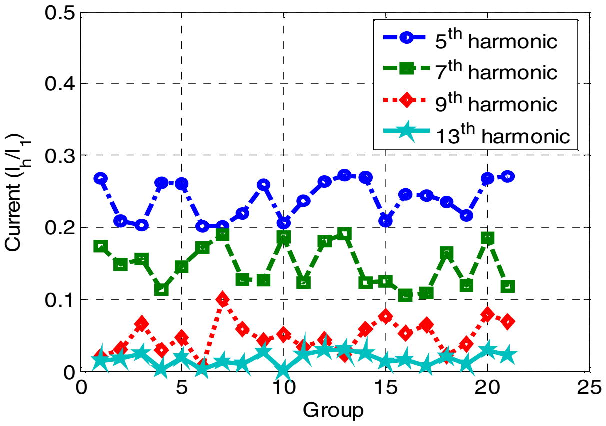

Figure 9- Example of harmonic evolution report.

5 Conclusions

The demand for electric energy in the recent years points to a sustained growth. In the same way, the cost of electric energy tends to increase proportional to the consumption. It is expected that the cost of electric energy, even for residential consumers, will be differentiated for each hour in the day and the consumption profile. In parallel, in the context of the relationship supplier-consumer, we observe a large demand for information about the quality of the supplied electric energy. Also, detailed periodic reports about power consumption and energy quality along the day and/or seasons of the year can be used to optimize the demand of electric energy.

The EEQ meter proposed in this work aims at providing a viable technical and economical alternative to face current and future challenges of the energy market in Brazil. The proposed instrument can be easily adapted to meet the standards of other countries.

Reconfigurable logic for local processing allows a dramatic minimization of the data generated by the meter, leading to a faster interpretation of the status of the electric network. Such performance is possible thanks to the parallel processing and reduced computation time, inherent to a FPGA hardware implementation.

The use of reconfigurable logic for this class of application was adequate, since it was able to provide an efficient solution, satisfying the project requirements and constraints. In the same way, it is expected that this technology can be a feasible alternative for practical problems that require high computational power and real-time response.

We expect that this work can contribute to the diffusion of this technology in electric power systems measurements.

Future work will include: tests to evaluate the performance, regarding to the processing speed for high sampling rates, and integration of the EEQ meter in residential, commercial or industrial environments aiming at its integration in a power management system.

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