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An embedded system approach for energy monitoring and analysis in industrial processes

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ABSTRACT

This paper presents the development of a low cost embedded system targeted to energy management in industrial environments. The main objective of this study is a methodology for monitoring, acquisition and analysis of electrical parameters using digital signal processing (DSP) techniques. For this task, a system (hardware and software) responsible for the acquisition records the input signals using low cost technologies, such as microcontrollers, DSP platforms and embedded system like ARM System-on-Chip (SoC) Architecture. Finally, for data analysis, two applications were created: one using the Matlab® software, and another derived from the first, to run on the embedded device. Both applications used Discrete Wavelet Transform as primary technique of disturbances detection. As a result, it is shown a complete system for monitoring and analysis of electrical parameters, serving as a tool to aid the energy management in industrial processes.

1. Introduction

Electrical Power Quality (EPQ) has become a growing and common concern to electricity companies (state concessions, electrification cooperatives) and consumers in general [17,28]. This growing interest in EPQ is due mainly to the technological evolution of electronic equipments, widely used in various sectors of activity (industrial, commercial and residential). This development resulted in more sensitive to electrical disturbances equipments [10]. These disturbances are mainly generated by the application of power electronics in several industrial processes, such as those involving the automation and energy conversion (AC/DC - Alternating Current to Direct Current).

The study of power quality as well as improvements in Energy Efficiency (EE) in electrical systems encompasses the analysis, diagnosis, and the proposition of possible solutions for the identified problems and the technical-economic evaluation [17]. For Musolino et al. [20] high efficiency energy storage systems permit energy recovery, peak shaving and power quality functions. Energy efficiency contributes significantly in reduce energy security risks and emission problems [11]. According to Garcia et al. [10], previous studies in energy generation and consumption field have shown that technical, commercial and financial losses sum up costs totaling billions of dollars a year worldwide, and its main cause is associated to the EPQ. Thus, one should establish joint actions between electric utilities, consumers and equipment manufacturers. For Hackl and Harvey [12] it is important to involve all companies within the cluster in studies to a more resource efficient and competitive production. Therefore, the problems of power quality are diagnosed and solved early in the projects elaboration. However, it is of great importance that corrective actions and awareness programs for the wise use of electricity should be applied and maintained permanently.

Thus, actions are necessary to establish energy efficiency, once they represent socioeconomic activities that aim to provide better power consumption (hydraulic, electric, gas, fuel). Therefore, seeking for alternatives and improving the efficiency of industrial processes are for industrial managers, rather than a sense of necessity, a matter of survival in the market [10,26,27]. The sustainable development of an industry is directly connected with energy efficiency [23]. The economic energy efficiency is a factor which is linking with other macroeconomic variables [31]. The reduction of energy consumption, besides being important to preserve the natural environment, as it reduces the need to increase supply, also provides financial returns for companies.

It becomes important that industries have effective management of energy demand consumed daily, so avoiding energy waste as a decrease in quality. However, given that the EPQ can reach the consumer with an excellent standard of quality, but with incorrect

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management, or even problems arising from the own infrastructure of the company, may imply in the reduction in the quality of the energy consumed in the industrial process. In this context, the focus of this work is the development of an embedded system (ES - hardware and software) capable of capturing, storing and analyzing information related to consumption and power quality in industrial systems. Furthermore, a method to evaluate the applied EPQ parameters is proposed, mapping in detail the power consumption in an industry (organization being researched), identifying the sectors of greatest consumption, detect and classify disturbances, searching for possible solutions.

2. EPQ disorders detection using the wavelet transform approach

According to Solórzano [28] the EPQ refers to a wide variety of conducted electromagnetic phenomena that characterize the voltage and current at a given time and location of the electrical system, directly affecting the energy efficiency of industrial processes.

Thus, the EPQ has three quality levels, namely: quality of customer service, service quality and product quality. The quality of customer service refers to the unauthorized charges, fees, service time and more. The quality of service is related to the operation and maintenance of the electrical system, providing to customers the minimal disruption acceptable. As for product quality it has a technical focus, regarding the compliance of the product itself, the availability of electric power with balanced sinusoidal voltages and with constant amplitude and frequency [4,8,10].

According to Deckmann and Pomilio [3] it is necessary for technicians or experts a research to diagnose the causes of the problems related to power quality. As it comes to diagnosing a problem of electromagnetic compatibility or the search for indicators of electrical parameters outside standards, this research may involve issues that go beyond a simple technological problem.

The EPQ refers to a wide variety of conducted electromagnetic phenomena that characterize the voltage and current at a given time and location of the electrical system. Thus, the quality of energy in a particular region of the electrical system is adversely affected by a wide variety of disorders [3,8,28], as: (i) transients (impulsive and oscillatory); (ii) short duration variations (transitory outages, voltage sags and voltage jumps); (iii) long duration variations (sustained interruptions, undervoltage and overvoltage); (iv) waveform distortion (voltage cut-off, harmonics, noise); and (v) voltage fluctuations and frequency variations.

For Ferreira [7] the identification and classification of power disturbances is an important step in the process of monitoring the EPQ, since it can directly contribute to identify the causes of the disturbances. Now the classification should be preceded by the step of detecting disorders. Various techniques can be used, as the average value, the Discrete Wavelet Transform (DWT), the Fourier Transform (FT) or Fast Fourier Transform (FFT). Even computational intelligence has been applied in the detection of disorders in EPQ [5,24,25]. Thus, functions or algorithms which permit the extraction of its characteristics are necessary to identify a disorder [10]. This way, the following methods are explained for identifying disorders: (i) RMS value calculation; (ii) Instantaneous Euclidean Norm; (iii) Application of Discrete Fourier Transform; and (iv) Application of Wavelet Transform.

The Wavelet Transform has some peculiarities that make it suitable for EPQ event detection in EPQ. One of these peculiarities is the behavior of these transform coefficients when the signal presents singularities. It is noteworthy that singularities in the case of EPQ can be understood as the moment of an event occurrence (switching capacitors, voltage sags, voltage interruption, etc.). When the presence of singularity, the coefficients tend to generate local peaks in each of the scales. Connecting these peaks at different scales, we obtain a line, known as *maxima line*. This line converges to the instant of the singularity occurrence.

In other words, the Wavelet Transform is used when it is necessary to locate individual events in the time domain [13], whereas the classical method of spectral analysis of frequency using Fourier Transform is suitable for periodic signals in steady state. This transform has its continuous (CWT) and discrete (DWT) variants. For Filho and Garcia et al. [9,10] the signal frequency components can be separated using wavelet decomposition filters. The result obtained when using the high-pass decomposition filter allows obtaining what is known as the detail coefficients in the wavelet domain, and the sequences of detail in time domain (Fig. 1).

According to Ferreira [8], the effect of the scale change of a signal can be best interpreted using the concept of resolution, this being achieved using filters. The filtering process used for the DWT presents an embodiment of the Multiresolution Analysis (MRA) technique proposed by Mallat [18], resulting in the combination of a scale function $f_{(t)}$ and a function wavelet $\psi_{(t)}$. This process is based on filtering a signal to be analyzed through high-pass and low-pass filters, providing versions of the original signal regarding the coefficients of wavelet functions and scale functions, or approximations and details, respectively [19].

The definition of a DWT function f by wavelet ψ is:

$$TWC_f^{\psi}(a,b) = \left|a\right|^{\frac{-1}{2}} \int_{-\infty}^{\infty} f(t)\psi_{ab}(t)dt \tag{1}$$

or,

$$(TWC)(a,b) = \left|a_0^m\right|^{\frac{-1}{2}} \int_{-\infty}^{\infty} f(n)\psi\left(\frac{t-b}{a}\right)dt \tag{2}$$

Thus, from the engineering point of view, DWT is no more than a digital filtering process in the time domain (discrete convolution), followed by a reduction of the number of samples (*downsampling*) by a factor of 2 [29]. Basically, the TWD function decomposes a signal into multiple frequency bands without losing information in time, thus providing an uneven division of the time-frequency plane. The same short intervals attributes in time for the high frequency components (details) and larger intervals to low frequency components (approaches). This division provides a better representation (resolution) of the signal in the areas of frequency and time [19], as shown in Fig. 2a. The One-Dimensional DWT implementation is shown in Fig. 2b.

A practical example of TWD usage can be seen in Fig. 3. The wavelet decomposition *S* (original signal in addiction to noise) results in the *cA1* and *cD1* outputs to the first level of decomposition. Applying another decomposition level for *cA1* we have the *cA2* and *cD2* signals. It is possible to observe an improvement in the quality of *cA2* signal relative to *S*[19].

3. Related works

Several works have been developed by academic and scientific communities in the context of EPQ. They typically target the development of techniques, methods and systems, that aim to monitor, analyze and measure related events. Some of these studies are based on certain mathematical tools such as Wavelet Transform and Fourier Transform [30,13]. This Section gives some background on these works and compares them.

Leborgne [17] in his dissertation presents an alternative