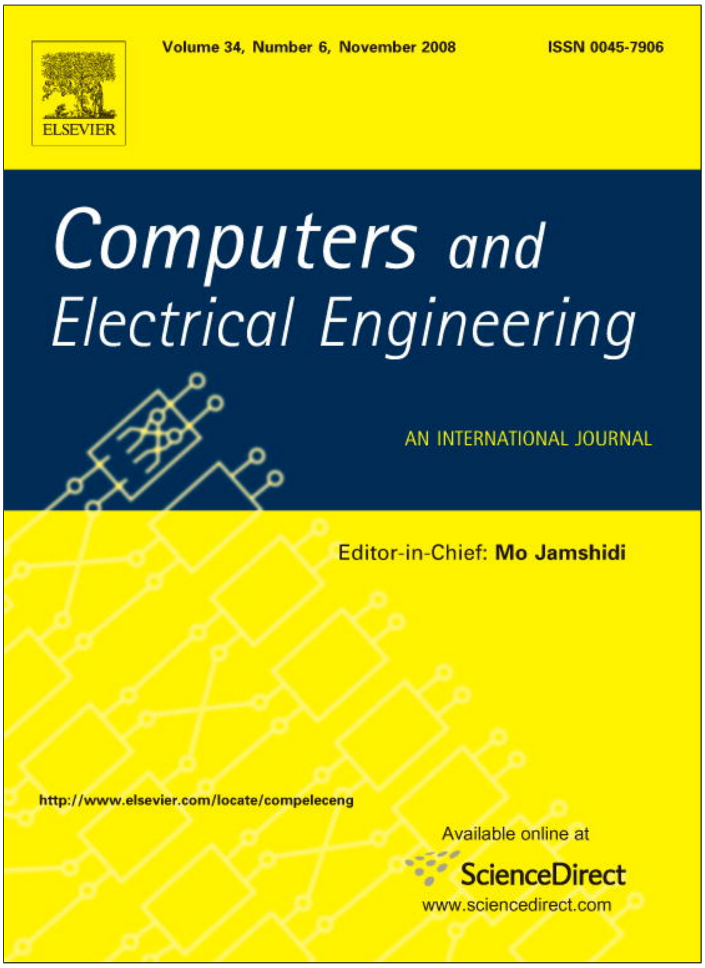
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Hardware and software architecture for power quality analysis

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Abstract

This paper presents a novel concept for power quality hardware and software architecture. Software tools related to detection, classification and characterization of power quality events can be integrated into a Distribution Control Center in which the interconnection between different subsystems is being carried out through the Internet allowing flexibility to the system. This system is implemented using wavelet analysis applied in all proposed algorithms. Different power quality events are taken as examples to illustrate the capabilities of the proposed method. The obtained results reveal that the proposed architecture is feasible to be implemented as an integral part of a control center system.

The proposed system has the property of fast and accurate detection and classification of any power quality disturbance event and introduces a new PQ index determination that allows characterizing any type of disturbance including the non-periodic signals.

Keywords: Power quality; Wavelet transform; Control center applications

1. Introduction

The deregulation process that is taking place in the electric power industries around the world will make the issue of the electrical Power Quality (PQ) delivered to consumers an object of great concern. Since the electric power supply industry is being deregulated, the commitment to supply high quality electricity is governed primarily by the contractual agreement between the supplier and the consumer. The enforcement of the contract can only be achieved if the status of power quality is known throughout the entire contractual period. Hence, utilities need to initiate aggressive programs to address power quality issues in their systems, undertake transient and harmonic in-house analyses, reduce costs and increase the speed of their calculation process. Therefore, it is desirable that a proper unified system be developed, that is capable of observing power quality phenomena, processing and analyzing data, as well as conducting proper modelling and data simulation.

One method to achieve these requirements is to incorporate the PQ system into the Distribution Control Center (DCC), thus allowing the utility dispatcher to inform their customers about the location of the

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disturbance is originated and who is responsible for the event. In addition, it must allow the dispatcher to determine whether the utility fulfills the imposed target indices.

One critical aspect to achieve power quality studies in a DCC is the ability to perform automatic power quality monitoring and data analysis. To satisfy these requirements, considerable effort should be expended to enhance PQ assessment methodologies. More sophisticated algorithms should be incorporated and better monitoring systems that include automatic monitoring, data collection, and feature extraction should be developed. In addition, better communication between the different systems should be adopted.

Several papers have emphasized these needs. A monitoring system based on secondary stations and communications with a host computer located at the DCC is proposed in [1]; the integration of power system modelling, classifying, and characterizing power quality events is suggested in [2]. A scheme to construct a system for real time detection and identification of different types of PQ events is recommended in [3]; the needs of an integrated PQ monitoring of a distribution system is also highlighted in [4], and in [5] the need of a unified software approach for PQ assessment and evaluation is strongly advocated.

The aim of this paper is to propose a new hardware and software architecture for PQ to be incorporated as an integral part of the Distribution Control Center. This system allows the interconnection between the DCC and the monitor systems located at remote substations and is capable of detecting, classifying and characterizing PQ events in the same environment.

The paper is organized as follows: first, Section 2 describes the proposed PQ monitoring system; then, Section 3 explains the overall software architecture developed. Sections 4–6 present the detection, classification, and characterization modules implemented and finally, Section 7 highlights the most important conclusions.

2. Monitoring system description

Fig. 1 presents the proposed system showing the interconnection of different subsystems through the Internet using the Transmission Control Protocol/Internet Protocol (TCP/IP).

The software located at the control center initiates the sequence by sending a synchronization signal, so that computers placed at the different substations can start the monitoring process. Each computer is tasked to

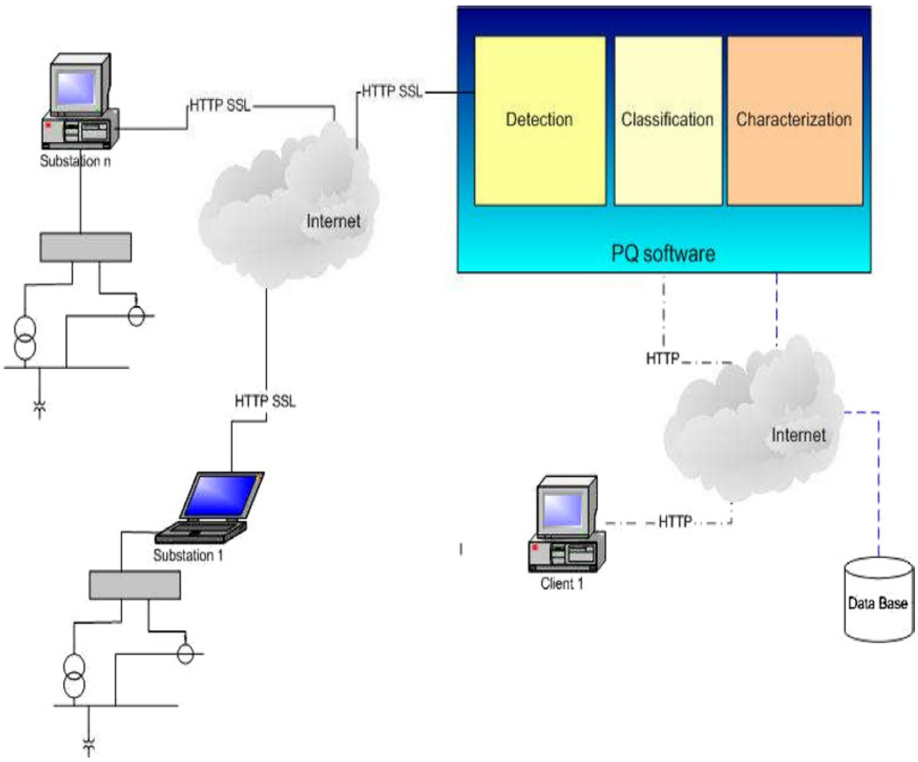


Fig. 1. PQ monitoring system.

record the various power quality events and store the information in the form of sampled data. This data is saved in the local database and is also sent to the control center through the Internet via a secure connection.

The main software package is located in the control center, which has the capability of detecting, classifying and characterizing the signals. The salient features of the system include (i) a centralized database to save all relevant information, (ii) a user-friendly interface that is designed to help dispatchers operate the software and (iii) secure Internet access for customers to access certain critical information. Based on this information, customers can monitor the quality of the system and review when a disturbance is related to them. The system is described in detail in the following sections.

3. Software architecture

The Graphical User Interface and Database Management Subsystem are two components of this system. The "Graphical User Interface" provides a friendly environment to use the program, which communicates through the Internet to a database server where the database management subsystem is located. The "Database Management" subsystem facilitates saving of data, retrieval of information as well as exchange of internal or external data. Due to space limitations, these two interface modules are not described in this paper, but they follow industry standard conventions.

Fig. 2 shows the main program panel, which also represents the structure of the software implemented. In this figure the four main modules can be visualized. These modules represent the main capabilities of the program:

- Signal generation/selection.
- PQ analysis module.
- Norms and Standards.
- Analysis of individual signals.

The first module, "Signal generation/selection" enables users to decide which signal will be processed. These signals are not only the sampled data provided by the monitoring system but also includes test signals that the user can generate in this module. The user can generate any type of PQ event by selecting start time, end time, phase, and amplitude value.

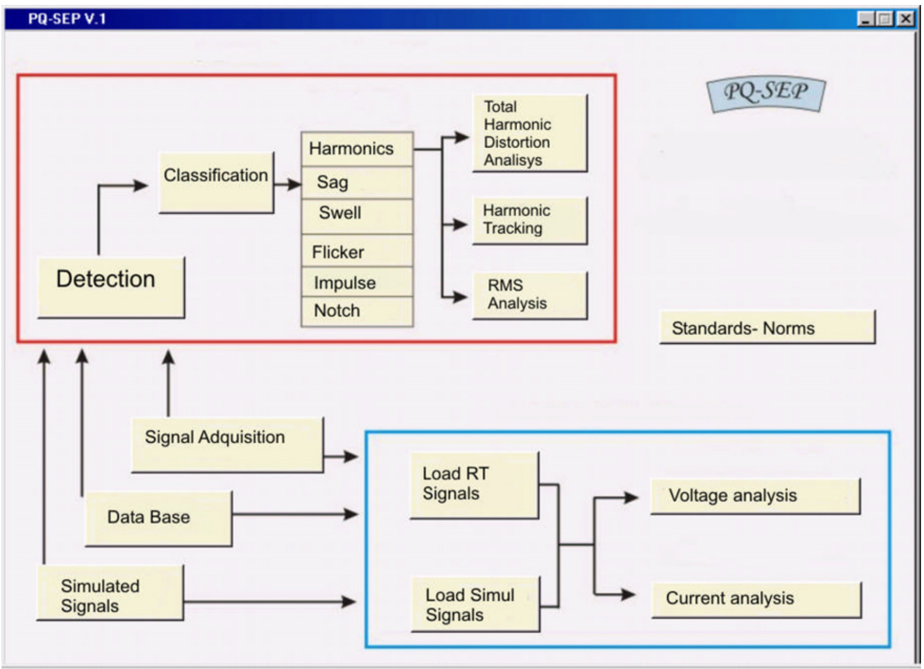


Fig. 2. Software architecture.

The second and the most important module of the software is the "PQ analysis module" which will be described in detail in the following sections. It is generally noted that the activities of detecting, classifying, and characterizing of power quality events are closely related and interdependent. However, for clarity, this module is divided into three sub-modules: Detection, Classification, and Characterization.

The application modules "Detection" and "Classification" automatically detect and classify the type of disturbance captured in the recorded or simulated waveforms. The types of disturbances include voltage sags, swells, harmonics, notches, flickers, and impulses. After the disturbance is detected and classified, the waveform is further processed by the "Characterization" module, where different sub modules have been designed to analyze the various types of events. The software automatically selects the appropriate sub module for computing parameters relevant to the event.

Parts of the implemented algorithms are referred to in previous papers [6]. Sections 3–5 give more details on the application modules "Detection", "Classification," and "Characterization", respectively.

The third module "Norms and Standards" allows the user to review the standards and norms that apply to the related system. Finally, there is a module entitled "Analysis of individual signals" which allows users to generate simulated waveforms, and to visualize the simulated or recorded waveforms. The software used for the communication as well as the main program is written in C/C++, however, several of the implemented algorithms are modules written in Matlab [7].

4. Detection

This section describes the module "Detection" implemented in the program. It is based on the wavelet transform (WT) since its capability for signal classification and identification is proven [8]. The detection process has two modes of operation: automatic or manual. The automatic detection mode is mainly used for real time application and utilizes the recorded signals received from the substation modules. The manual mode can use recorded or simulated waveforms which are available in the database.

Once the mode and the signals are selected, the detection process starts; the signal is decomposed into wavelet coefficients using wavelet transform, and based on these coefficients, the program detects whether any of the PQ disturbances is present in the signal and determines the duration of the event.

To show the capability of the detection process; Fig. 3 illustrates a PQ disturbance identified by the program. This example shows a voltage dip, the acquired signal is represented by $x(t)$ in the figure. A window of 0.4 s is selected for better preview.

The detailed coefficients d_1 and d_2 identify the presence of the impulses; these signals are the ones that the program uses to automatically detect the presence of a perturbation. The duration of the perturbation is calculated by comparing the coefficients with a threshold signal. The approximation scale a_4 and the detail coefficients d_4, allow estimating the harmonics in the signal. In this case, the evaluation of the approximation scale shows the presence of a voltage sag in this signal.

Once a disturbance is detected, the next step is to transfer the decomposed signal to the "Classification" module.

5. Classification

Following a PQ disturbance detection, the sub module "Classification" is activated. The classification algorithm is based on the wavelet transform coefficients and an Artificial Neural Network (ANN) algorithm [2]. The learning vector quantization (LVQ) method is selected to train the network. Fig. 4 illustrates the main blocks of this process.

Given a signal $x(t)$, the signal is decomposed into wavelet coefficients c, and d. Subsequently, the input signal vector is built based on the energy associated with these coefficients. The following equation shows this relation

$$E^2_{\text{signal}} = \sum_{k=-\infty}^{\infty} |c_k|^2 + \sum_{j=0}^{\infty} \sum_{k=-\infty}^{\infty} |d_{j,k}|^2 = E^2 c_0 + \sum_{j=0}^{J-1} E^2 d_j \quad (1)$$

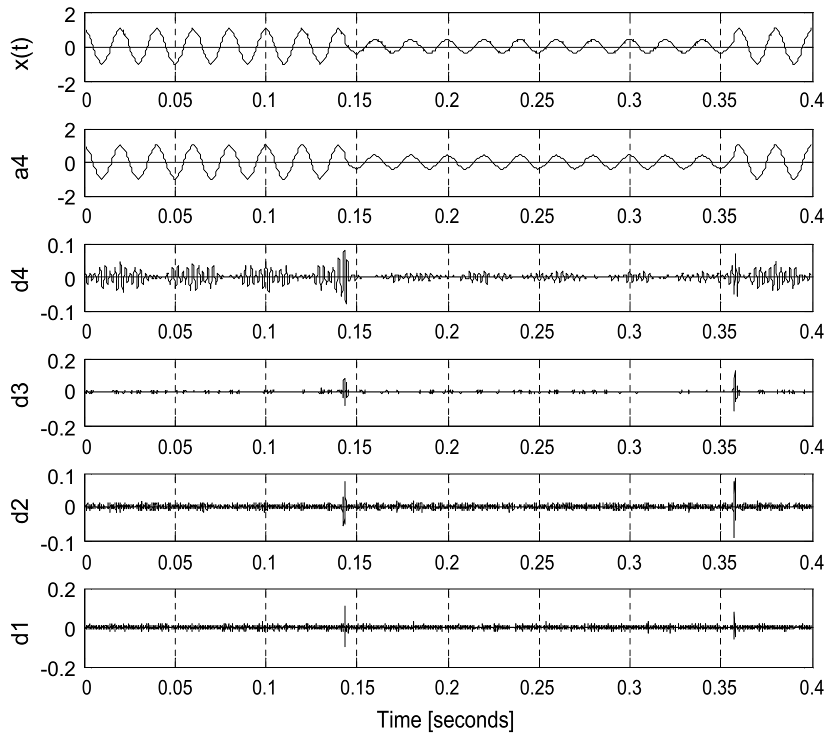


Fig. 3. Wavelet based detection.

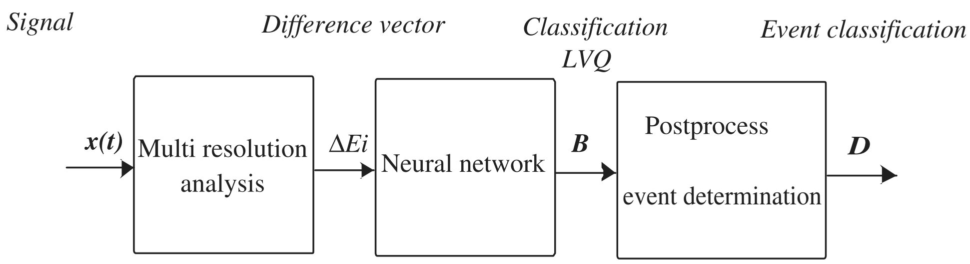


Fig. 4. Classification scheme.

where:

$$E^2 d_j = \langle d_{j,k}, d_{j,k} \rangle = \|d_j\|^2, \text{ and} \tag{2}$$

$$E^2 c_0 = \langle c_{0,k}, c_{0,k} \rangle = \|c_0\|^2. \tag{3}$$

This energy vector is compared to the energy vector produced by a pure sinusoidal signal, and the difference vector ΔE is the one used as an input to the neural network. Fig. 5 shows the scheme of the multiple layer neural network implemented in the classification module. During the training process the event represented by the input vector is known, therefore the group of neurons that needed to be activated is determined and the weight vectors $w_i[n]$ are tuned.

For a specific input signal C, the weights are updated during the training process until the event is accurately classified. The updating rule is represented by

$$W_c[n+1] = \begin{cases} \frac{w_c[n]+\alpha\Delta E[n]}{\|w_c[n]+\alpha\Delta E[n]\|} & \text{if } \Delta E[n] \text{ is properly classified} \\ \frac{w_c[n]-\alpha\Delta E[n]}{\|w_c[n]-\alpha\Delta E[n]\|} & \text{if } \Delta E[n] \text{ is not properly classified} \end{cases} \tag{4}$$

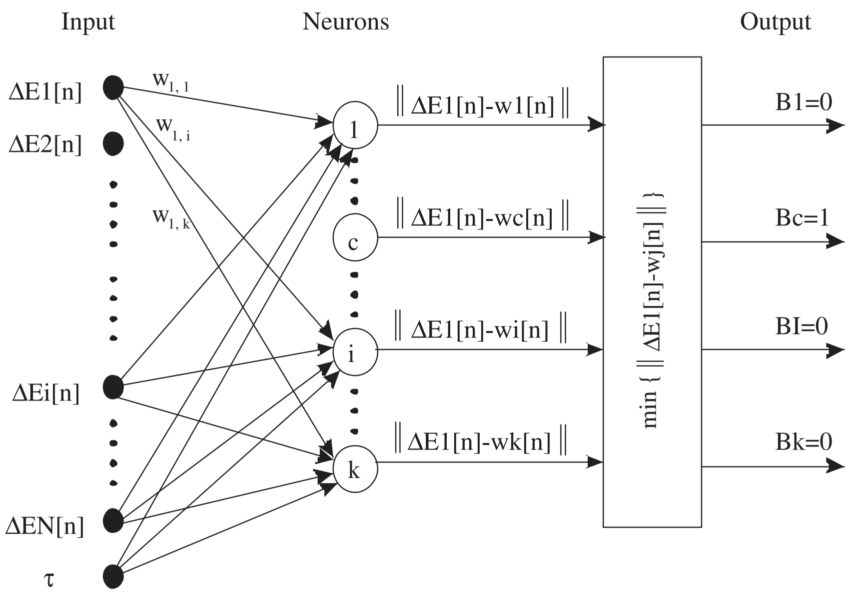


Fig. 5. ANN classification.

where α is the learning function; The learning process finishes when all input training cases are classified with a given precision. consequently, the logic of the output vector B is used to identify the type of perturbations present on the signal.

Fig. 6 shows the results obtained using this method. In this example a neural network with five banks is selected. The post processing for proof accumulation and decision is implemented using a simple vote scheme. The program captures the signal at 56th minute from the start point, where the voltages at phases R, S and T are shown. The perturbation is classified as a swell, which can be seen in the dynamic window displayed in the lower part of the figure that is a frequency vs. time curve.

In the upper left window the voltage signal is displayed, and every perturbation is reported and presented per phase as shown in the bottom part of the figure. These windows report the events per phase, including the start and the end time. In addition, the THD value, the RMS value and the most recent event are presented.

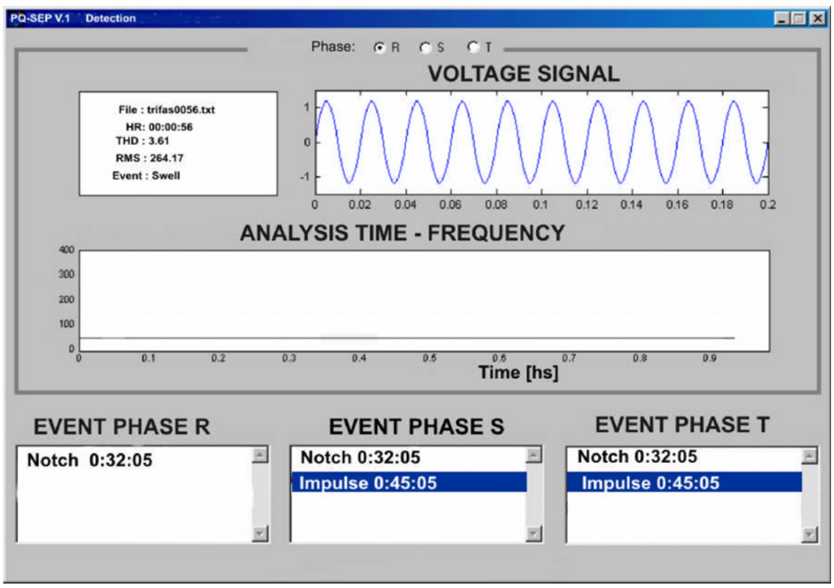


Fig. 6. PQ classification.

Furthermore, results can be seen in a more compact way in the display shown in Fig. 7. This window reports the events and their time extent, and each perturbation is represented in a different color for better viewing.

6. Characterization

In order to identify and define acceptable limits of distortion levels, standards have been established [9–12] and several indices have been proposed condensing the information provided by voltage and current signals from complex time and frequency domain into a single number [13].

The characterization process depends on the type of perturbation that the previous step classifies. For illustration purposes this section will focus on the harmonic characterization.

The program allows to characterize the perturbation, which is already detected and classified, using two different methods. The classical one based on the total harmonic distortion (THD) index, which is the most commonly used index [14], utilizes harmonic components of currents or voltages, which are required to be periodic signals. Therefore, the condensation of the information associated with the signals that contain a quasi periodic or non integer multiple of power frequency terms, may be misinterpreted. This happens in many cases including industrial loads [15,16]. Therefore, a more complex method based on the wavelet total harmonic distortion (WTHD) index is also implemented. The WTHD can be defined as the square root of the ratio of the sum of squares of all the weighted coefficients details of the signals to the sum of squares of the lowest frequency band approximation coefficients. This index is defined as follows:

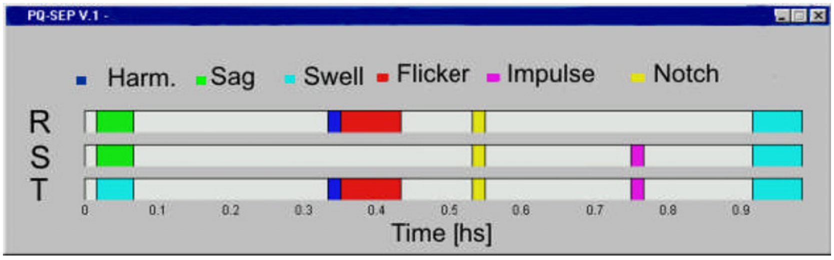


Fig. 7. Events display.

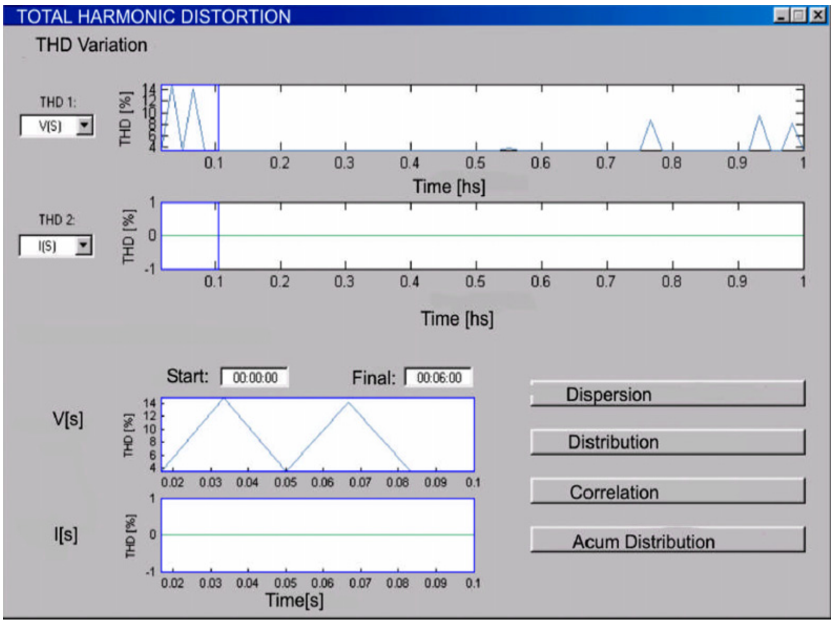
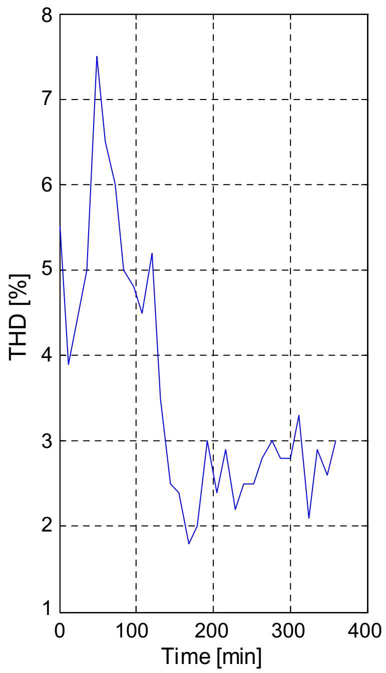


Fig. 8. Total harmonic distortion variation.



THD mean	3.6
THD std	1.5
THD max	7.5
THD min	1.8

Fig. 9. Total harmonic distortion statistics.

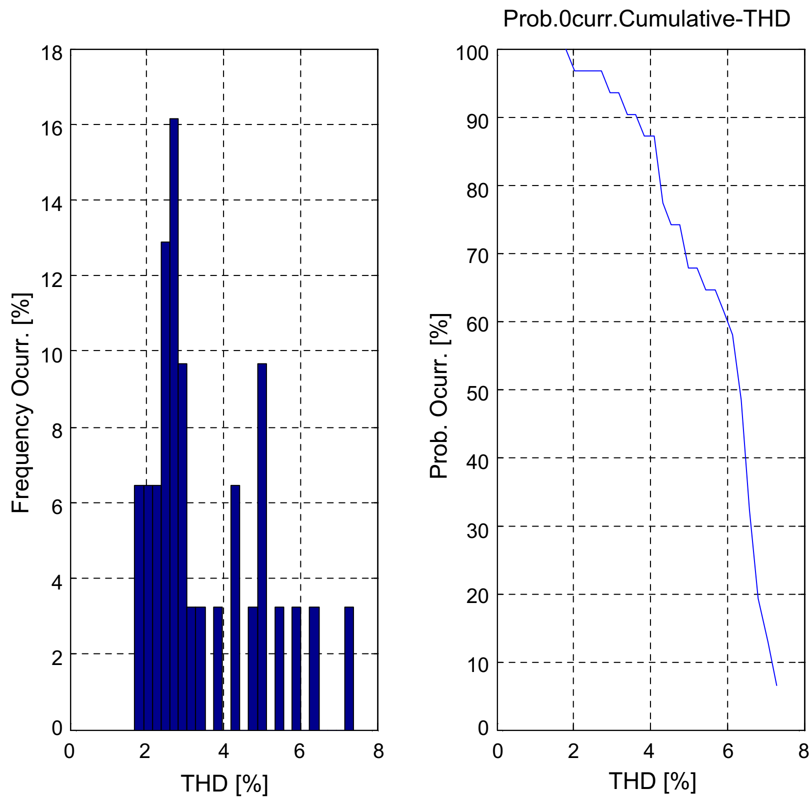


Fig. 10. Total harmonic distortion.

$$\mathrm{WTHD}_i = \sqrt{\frac{\sum_{j=1}^{J-1}\sum_{k=1}^{Nj} d_j^2(k)}{\sum_k a_j^2(k)}} \tag{5}$$

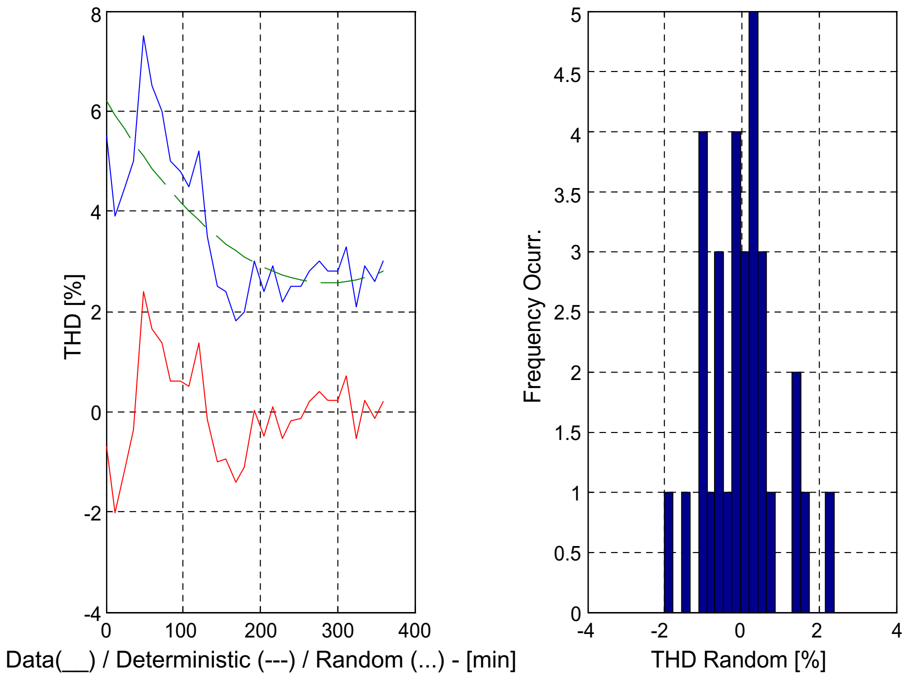


Fig. 11. Deterministic analysis module.

where J is the number of decomposition levels, d represents the coefficient detail at scale j,Nj represents the number of the points, and a_m represents the approximation coefficient at scale j. Details of this algorithm are described in [17].

Fig. 8 shows the THD calculation of a signal. In this example, the current and voltage distortion over a certain period of time is calculated.

In addition, the program provides a statistical module that furnishes additional information about the perturbation.

A recorded data from a bus containing a rolling mill is used as a test signal in order to show the features of the statistical module. The voltage level at the bus is 13.2 kV. The sampling rate is defined as one sample every minute, for a period of six hours. The mill runs for the first three hours. Figs. 9–11 are the screen captures of the output results of the program.

Considering that in this example the THD data follows a Gaussian distribution, the probability density function is calculated and the histogram is presented in Fig. 10.

Finally, a combined description of the statistical and the deterministic analysis is given along with a comparison of the two analysis, which are shown in Fig. 11.

7. Conclusions

A software and hardware architecture for power quality events detection, classification, and characterization is proposed and implemented. The hardware architecture is designed to be integrated into a Distribution Control Center. The proposed system has the property of fast and accurate detection and classification of any power quality disturbance event and introduces a new PQ index determination that allows to characterize any type of disturbance including the non-periodic signals.

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