Disturbance Analysis for Power Systems Based on LabVIEW Real-Time and Reconfigurable FPGA Modules Using Wavelet Transform

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Abstract - **This paper present a disturbance analysis monitoring system for the purpose of detection of disturbance analysis using Wavelet Transform (WT). The proposed system is based on the real-time capabilities of the Real-Time LabVIEW operating system and on a CompactRIO type real-time computer which contains a network of FPGA (Field Programmable Gate Array). The WT is used to analyze the quality of energy and to detect the transient phenomena characteristic of the quasi-periodic signals. The system achieves the storage of entries as TDMS (Technical Data Management Streaming) files and Word/Excel type automatic reports automatically sent by email at predefined addresses, contains an OPC UA (Open Platform Communications Unified Architecture) type server for communication with a hierarchically superior SCADA (Supervisory Control And Data Acquisition) type system, performs selective entry of the characteristic parameters into a database, contains a Webserver for Intranet/Internet access, for viewing the measured data, and for system management from anywhere, the application is connected to a Cloud-type platform. The disturbance analysis monitoring system has been tested using both simulated signals and real signals from a practical experiment.**

Cuvinte cheie: *calitatea energiei electrice, transformata Wavelet, FPGA, timp real, baze de date cloud.*

Keywords: *power quality, Wavelet transform, FPGA, real time, cloud database.*

I. Introduction

Electricity is probably the most important raw material used today in trade and industry. It is a product with a distinct feature, because it must supply a continuous flow, it cannot be stored in large quantities and cannot be subject to quality control before it is used. Electricity producers, distributors and consumers face multiple challenges in the area of energy in recent years. Due to the growing concern for environment, energy, and financial savings, it is essential for energy consumers to benefit from a modern, efficient, and intelligent system for monitoring the electrical grid and improving PQ (Power Quality) and its management. Thanks to network monitoring systems, providers are able to detect electrical anomalies (and their causes) at the same time providing better energy service to communities, while reducing the recurring losses and the effects of disturbances, such as material damages, deterioration of the lifetime of the equipment and loss of information [1-4].

PQ is becoming prevalent and of critical importance for power industry recently. The result of the increased use of microprocessors in appliances, office equipment and process controls is growing awareness of the disturbance analysis demands for equipment and the unpredictability of its supply. Transient phenomena are extremely critical since they can result in over voltages leading to insulation breakdown or flashover. The effects of these failures include: tripping of any protection device, which initiates a short interruption to the supplied power; complete damage to system equipment during the transient period, caused by excess current produced by transients; failures or malfunctions of various if such disturbances are not mitigated [5-8].

Wavelet Transform has been used in the area of PQ to carry out several studies aimed at detecting and locating disturbances, by analyzing sag, swell, interruption, etc. of non-stationary signals. These disturbances are “slow changing” disturbances, containing only the spectral contents in the low frequency range. Therefore, WT coefficients (WTCs) can be studied in very high decomposition levels in order to determine the occurrence of the disturbance events as well as their time of occurrence. Owing to this, the Discret Wavelet Transform (DWT) techniques have been widely used to analyze the disturbance events in power systems. Due to its capability of solving problems in many areas, computer science technology has been developing rapidly in this very modern era. High power signal processing has been made possible as a result of this progress in technology. DWT is one of the very important modern techniques widely used in signal processing tools especially for extracting the power disturbance signal [9-14].

Wavelets localize the information in the time-frequency plane; in particular, they are especially suitable for the analysis of non-stationary signals since they are capable of trading one type of resolution for another. Such properties have been found to be relevant for power engineering, where the wavelet transform is used for various applications, depending on the wide variety of signals and problems encountered, ranging from the analysis of the PQ disturbance signals to, very recently, power system relaying and protection. The extreme variability of the signals and the necessity to operate for each case in particular makes it difficult for power engineering phenomena to be dealt with. Power disturbance signals are also characterized by the fact that the information under consideration is often a combination of features that are well localized temporally or spatially (e.g., transients in power systems), requiring analysis methods sufficiently versatile to examine signals according to their time-frequency localization [15-21].

The proposed system presented in this article is based on the real-time capabilities of the Real-Time LabVIEW operating system and on a CompactRIO – National Instruments type real-time computer which contains a network of FPGA type reconfigurable logic gates providing great flexibility, reliability and speed of execution.

The DWT is used to analyze the quality of energy and to detect the transient phenomena characteristic of the quasi-periodic signals. The system contains a prefilter module for removal of spikes by using a Wavelet Denoising type module. The system achieves the storage of entries as TDMS files and Word/Excel type automatic reports automatically sent by email at predefined addresses, contains an OPC UA type server for communication with a hierarchically superior SCADA type system [22], performs selective entry of the characteristic parameters into a database, contains a Webserver for Intranet/Internet access, for viewing the measured data, and for system management from anywhere, the application is connected to a Cloud-type platform.

The paper is organized as follows: Section 2 describes the most used tool for the analysis of the quasi-stationary signals which occur during the study of the quality of electricity, i.e. the Wavelet transform and some simulations of the most common disturbances in the electrical network. Section 3 presents the implementation of the real-time system for electricity quality analysis and the software facilities for data management and integration into global Intranet/Internet networks. A practical example is presented in section 4, and section 5 presents the conclusions and the advantages of the presented system for electricity quality analysis, but also some perspectives for further development.

II. WAVELET TRANSFORM

Wavelet theory is a method for decomposing a function (signal) into various frequency components and study of each component with a resolution match to its scale. A wavelet is a small wave with the energy concentrated in time and gives a tool for analysis of transients, non-stationary, time varying phenomenon which generally occurs in the power system network.

Mother wavelets are oscillating function with a finite energy and average values of zero, i.e. $\int_R \psi(t)dt = 0$, where $\psi(t)$ is mother wavelet [9].

The signal can be represented in terms of wavelet function and scaling function as:

$$f(t) = \sum c_j(n)\phi(t-n) + \sum_n \sum_j d_j(n) 2^{j/2} \psi(2^j t - n) \quad (1)$$

Where: c_j represents level scaling coefficient; d_j represents j level wavelet coefficient; ϕ represents scaling function; $\psi(t)$ represents wavelet function; j can be any higher level wavelet transform and t is time.

DWT uses the discrete values of the signal in time domain. Mathematically the expression for DWT can be given as:

$$\psi_{a,b}(t) = \frac{1}{\sqrt{a_0^m}} \left(\frac{t - nb_0 a_0^m}{a_0^m} \right) \quad (2)$$

Where m and n are the integers which control the wavelet dilation and translation respectively, a_0 is a fixed dilation step parameter which should be always greater than one and b_0 is the position parameter.

The original signal is passed through a low-pass and high-pass digital filter $h_d(n)$ and $g_d(n)$. The coefficients of first level decomposition signal are:

$$cA_1(n) = \sum_k f(n).h_d(-k+2n) \quad (3)$$

$$cD_1(n) = \sum_k f(n).g_d(-k+2n) \quad (4)$$

When these signals pass through another low pass digital filter then second level wavelet coefficient can be obtained and this process we continued to calculate the "n" level approximation.

The wavelet coefficients are used for calculating approximation as well as the detailed version of original signal, in different levels of resolutions, in the time domain and these features is used for the detection and analysis of PQ events in power systems.

Next, this chapter presents the application of WT for the detection and analysis of virtual digital signals for sags, swells and transient impulses.

The voltage signals are generated and processed by using LabVIEW and Matlab environment software development. The sampling frequency is of 12.8 kHz with 256 samples per cycle for the supply frequency of 50 Hz. WT is applied to detect the voltage disturbances such as voltage sags, swells and transient impulses. The frequency bands of WT coefficients are shown in Table I.

TABLE I. FREQUENCY BANDS OF DWT COEFFICIENTS AT DIFFERENT LEVELS

Coefficients	Frequency Band (Hz)
d1	6400-12800
d2	3200-6400
d3	1600-3200
d4	800-1600
d5	400-800
d6	200-400
d7	100-200
d8	50-100
d9	25-50

The WT analysis of signals by using the Db5 wavelet for voltage sag, swell, and transient impulse, and the detailed coefficients at seven levels (d1 to d9) and approximation coefficient at level 9 (a9) are presented in Fig. 1, 2 and 3 respectively.

By analyzing the d1 coefficient, it is noted that for both the sag and the swell phenomenon, the start and end points are of 0.05 s (sample no. 640) respectively 0.15 s (sample no. 1920).

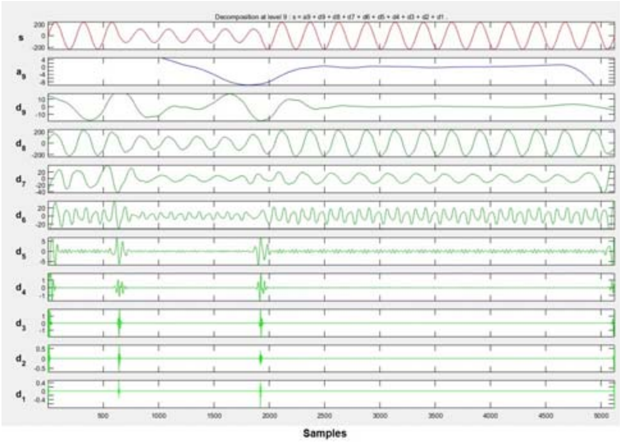

Fig. 1. DWT of voltage sag - detailed coefficients

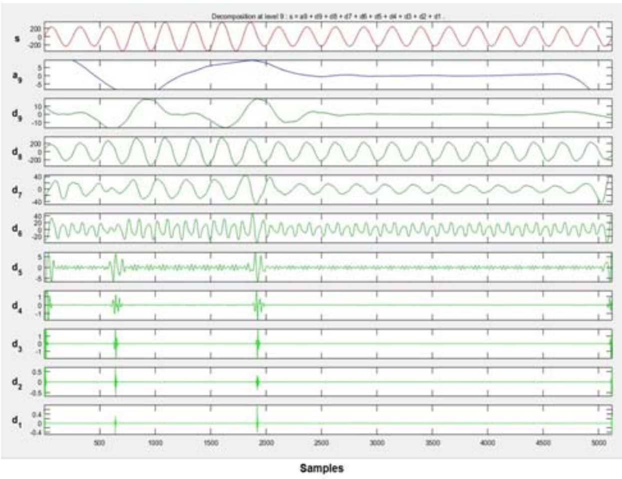

Fig. 2. DWT of voltage swell - detailed coefficients

In the case of transient impulse in Fig. 3, it occurs at time 0.0059 s (sample no. 76) and ends at time of 0.006 s (sample no. 77). Its duration is of 0.1 milliseconds; it may be considered as disturbance (see fig. 4) and will be rejected by using a WT filter with the software block diagram as shown in Fig. 5. The filtered signal is shown in Fig. 6. In practice such a spike or notch signal can be supplied by the electronic switching elements (e.g. IGBT).

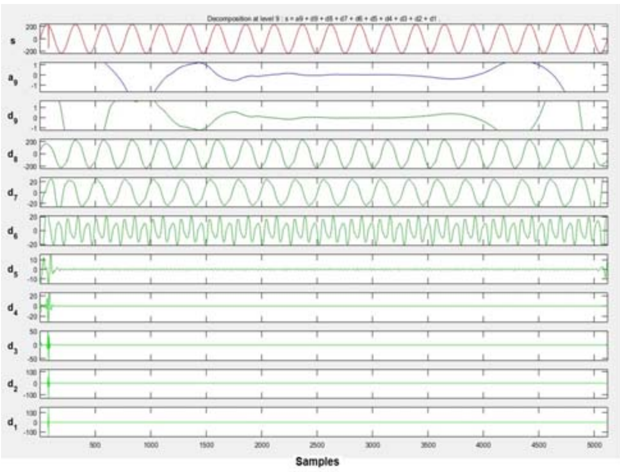

Fig. 3. DWT of voltage transient impulse - detailed coefficients

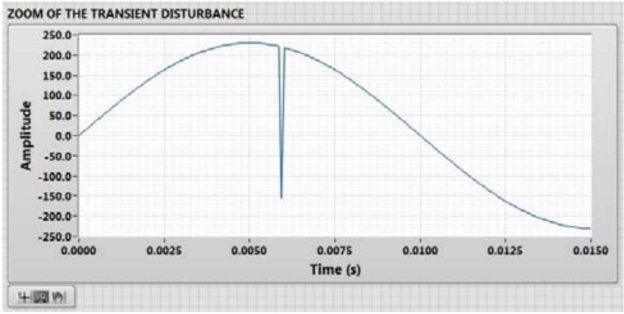

Fig. 4. Voltage transient impulse disturbance – zoom

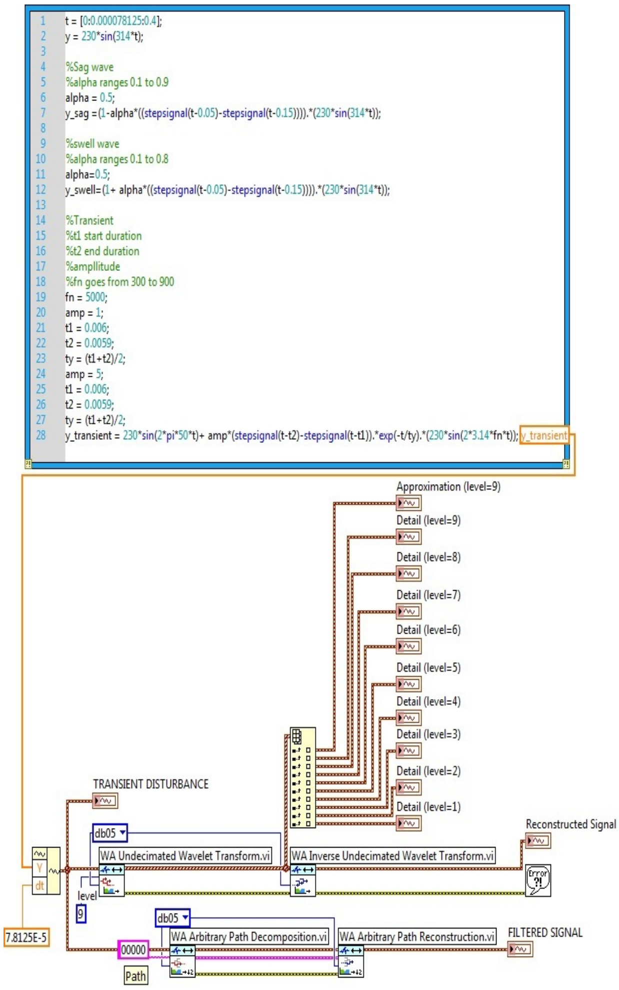

Fig. 5. Software block diagram of the DWT filtering of the voltage transient impulse disturbance

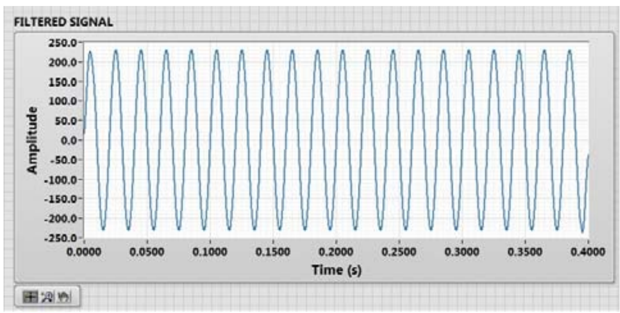

Fig. 6. Filtered voltage transient impulse disturbance

III. Hardware and Software Description

The general software architecture of the disturbance analysis monitoring system is shown in Fig. 7. The presented system is based on the real-time capabilities of the Real-Time LabVIEW operating system and on a CompactRIO – National Instruments type real-time computer which contains a network of FPGA , it uses an OPC-UA type server, TDMS type files, a MySQL type database server, and a Web Server.

CompactRIO is a reconfigurable embedded system containing three components: a processor running a real-time operating system (RTOS), a FPGA, and interchangeable industrial I/O modules. The CompactRIO-9030 from National Instruments is an embedded controller ideal for advanced control and monitoring applications with the features: 1.33 GHz Dual-Core CPU, 1 GB DRAM, 4 GB Storage, Kintex-7 70T FPGA, 4-Slot CompactRIO Controller. NI-9201 is a Voltage Input Module from C Series with the following features: ±10 V, 500 kS/s, 12-Bit, 8-Channel C Series Voltage Input Module. The acquired signals come from LEM LV 25-P voltage and AT100B420L current transducers.

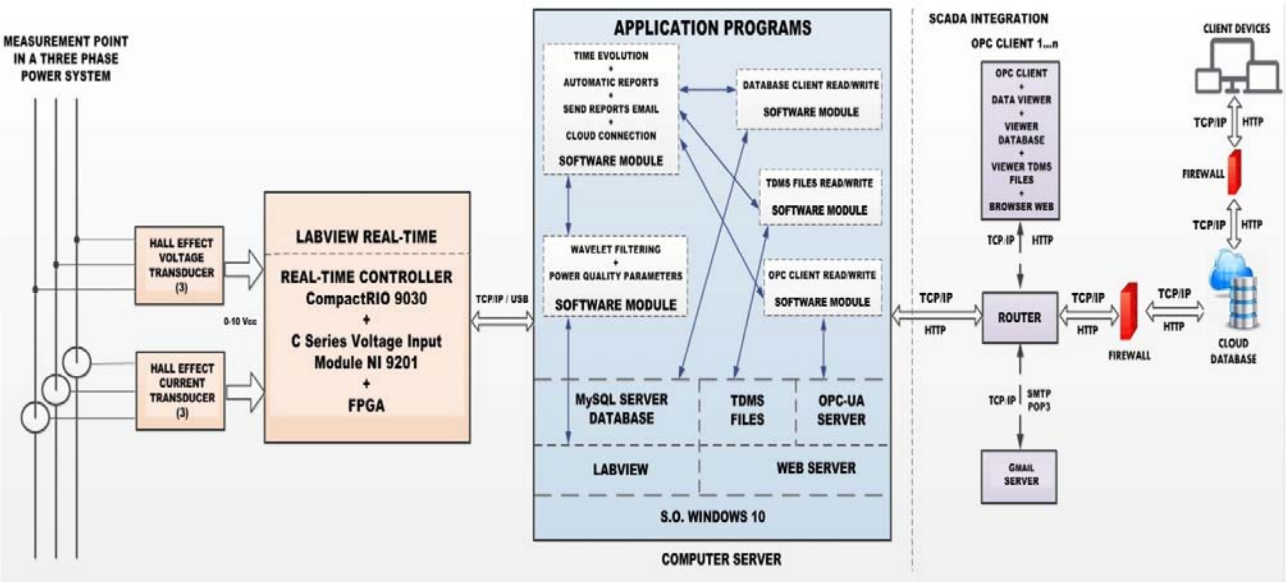

Fig. 7. The software architecture of the disturbance analysis monitoring system

The types of software modules of the PQ monitoring system, on the server machine are the following:

- The Time Evolution and Data Acquisition software module realize the primary data acquisition and the software interface of the computer Host is presented in Fig. 8;

- The Wavelet Filtering and Analysis module is the main module of the system, and allows the detection of the characteristic phenomena of the PQ using Wavelet analysis;

- The OPC read-write module; this module will provide intrinsic connection between the data acquired from input modules and the OPC server;

- The MySQL read-write module; this module will achieve MySQL type database query, where obviously data writing and reading are the most used functions;

- The TDMS read-write module; this module will manage data writing and reading in TDMS files;

- The Automatic Report and Send Email software modules realize the automatic reports with the detailed coefficients obtain from the Wavelet analysis;

- The Cloud Connection software module realizes the connection with the Cloud-type platform. The Cloud database interface and the software block diagram for connection to cloud platform and MySQL Server database.

A suitable development environment for the implementation of monitoring and SCADA integration applications is the LabVIEW environment, also referred to as G language, which is a graphical programming language using icons instead of lines of text to create applications. In contrast to text-based programming languages, where instructions determine the program execution, LabVIEW uses dataflow programming, where the flow of data determines the execution.

The global project three achieved in LabVIEW and the software block diagram of the Compact-RIO-9030 PFGA Target is presented in Fig. 9.

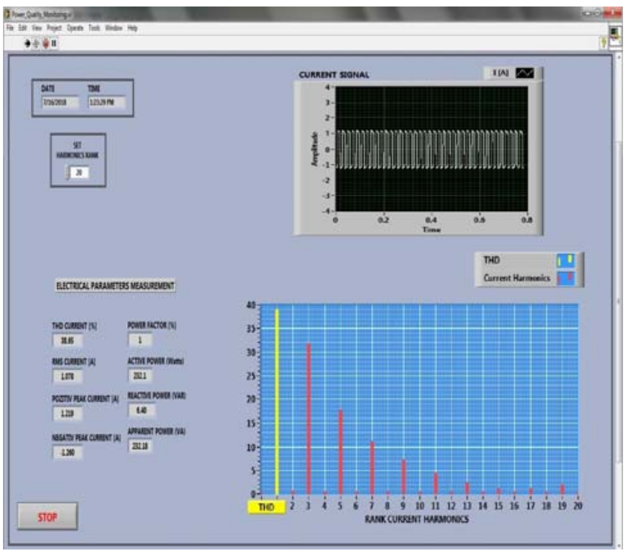

Fig. 8. The software interface of the computer Host

The initial filtering of the acquired signals consists of eliminating the transient impulses of less than 0.1 milli-seconds, and is performed using a 10 kHz Butterworth Filter, implemented in the FPGA target, in a loop that runs cyclically at 78 microseconds. The transfer mode of the data between the FPGA Target and the Host computer is achieved through the DMA (Direct Memory Access) transfer RT FIFO (Real Time First-In-First-Out memory buffers) type.

For SCADA integration of the presented application is used the OPC Unified Architecture (UA) which is a new communication technology standard. This new communication technology is based on the OPC and includes all the functionality of the OPC Classic. In OPC UA are improved the security and the easiness to connection of the non-windows platform [24].

The software interface for disturbance analysis monitoring system based on OPC UA Server is shown in Fig. 10 and contains: the software block diagram OPC UA Server SCADA integration, the software block diagram of the client write data toward OPC UA Server and the software block diagram of the client read data from OPC UA Server.

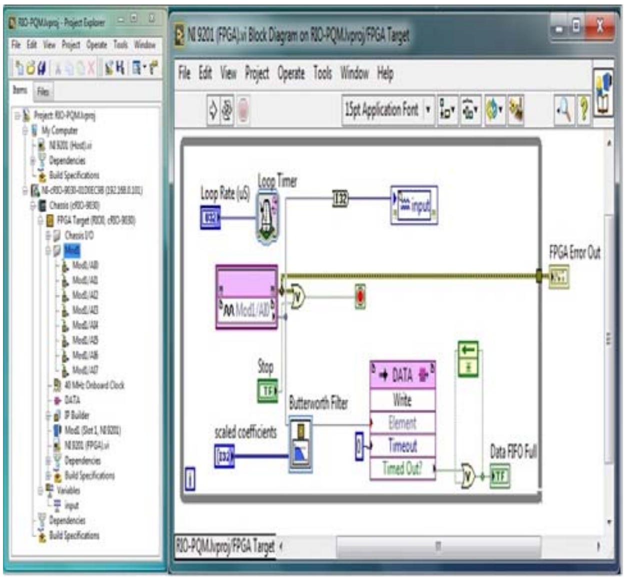

Fig. 9. The PQ monitoring project with the software block diagram of the Compact-RIO-9030 FPGA Target

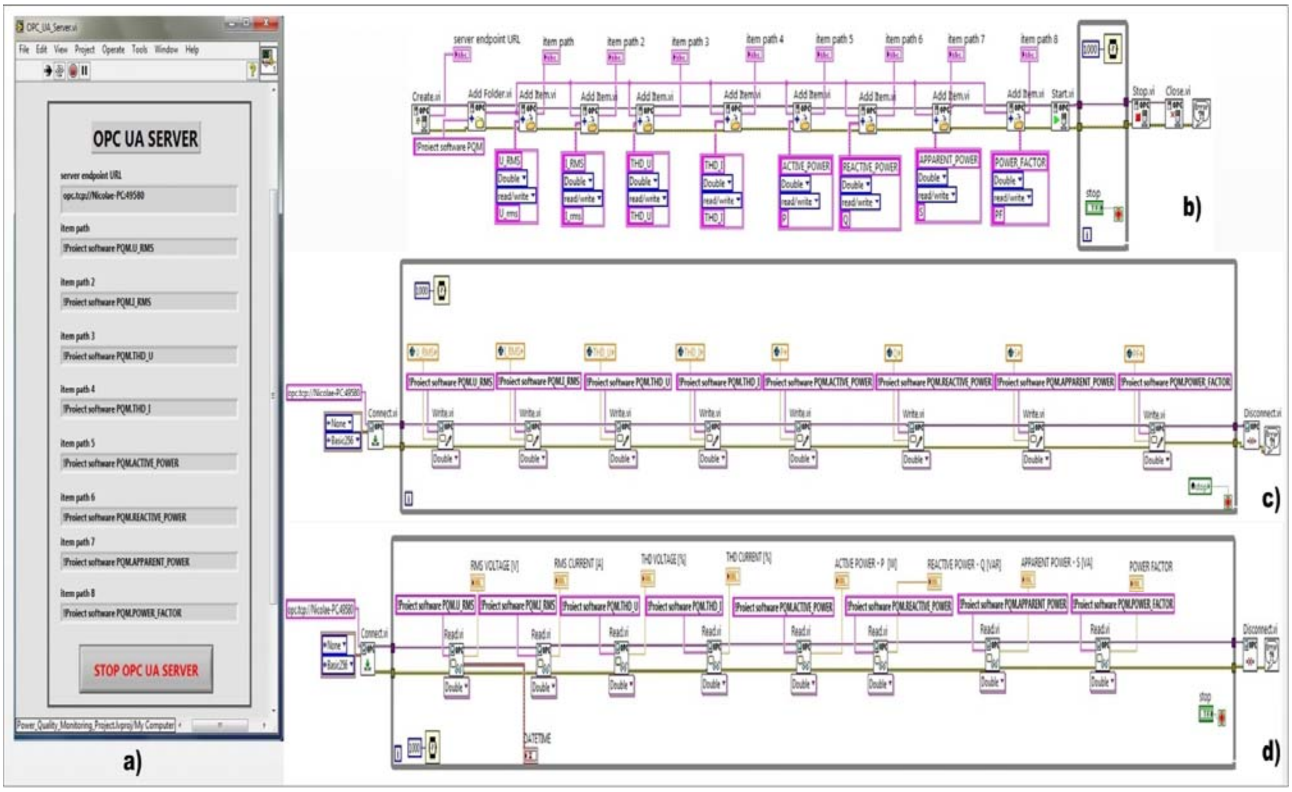

Fig. 10. Disturbance analysis monitoring system – SCADA integration: (a) OPC UA Server software interface, (b) Software block diagram OPC UA Server SCADA integration, (c) Software block diagram of the client write data OPC UA Server, (d) Software block diagram of the client read data OPC UA Server

For reading and writing the database of application is used a DataSources (ODBC) type connection.

A cloud database is a database that typically runs on a cloud computing platform, access to it is provided as a service. The dashboard editor is a powerful, flexible tool that helps you design the interface you require.

Fig. 11, (a) shows a sample of the database from which a Word type report can be automatically generated and printed, Fig. 11, (b) shows the Cloud database interface, and Fig. 11, (c) shows the software block diagram for connection to cloud and MySQL Server database.

The application program automatically generates emails with automatic reports at predefined addresses based on the support of ActiveX Containers, and ActiveX Events included in LabVIEW programming environment.

In Fig. 11, (d) is presented the software block diagram for the implementation in LabVIEW of the Send Automatic Report Email Module.

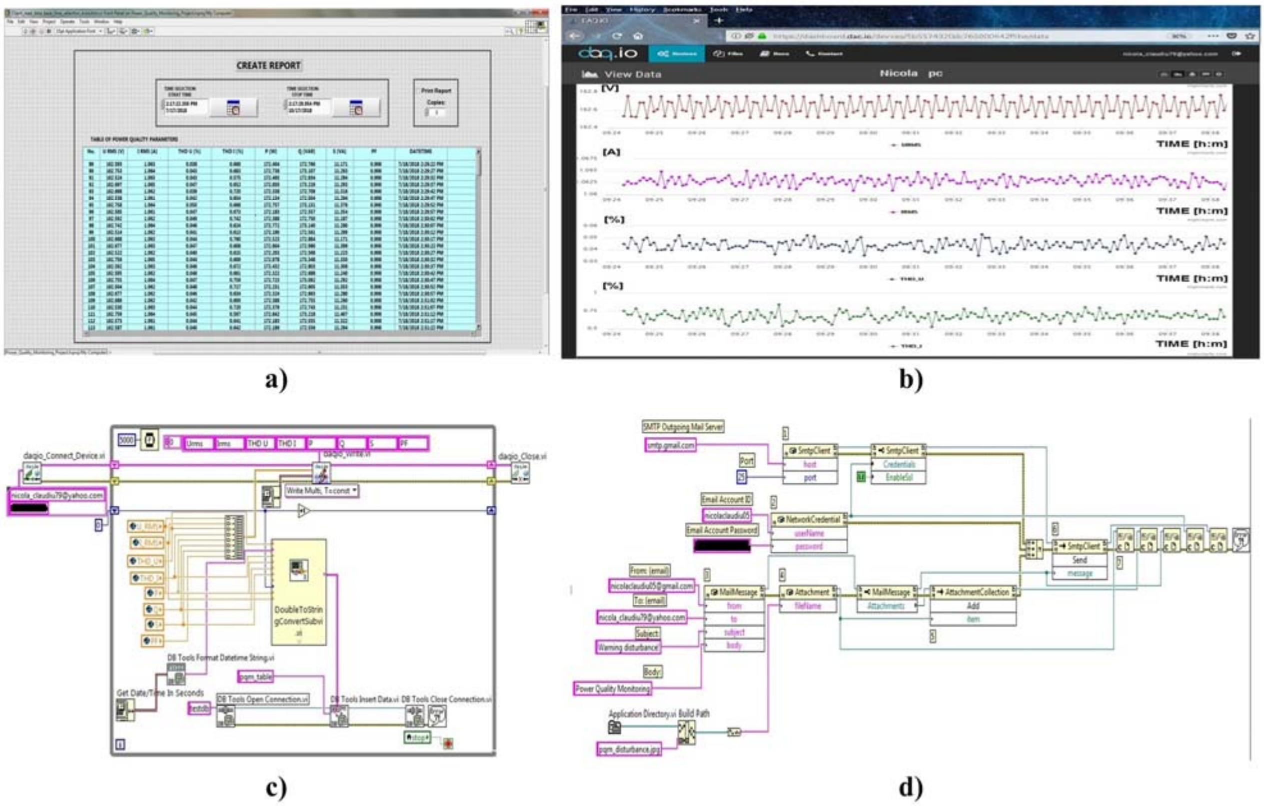

Fig. 11. Disturbance analysis monitoring system – connection MySQL and Cloud database and Gmail Server: (a) Database selection software interface, (b) Cloud database interface, (c) The software block diagram for connection to cloud and MySQL Server database, (d) Send Automatic Report Email Module software block diagram

The exchange of live data with other applications on different computers from Intranet/Internet is assured by an integrated Web Server. The method used to transmit data between Web Browser and Web Server is by type POST HTTP method.

In Fig. 12, (a) is presented the time evolution of PQ parameters using a Web Browser.

The reading and writing of global variables is achieved used a LabVIEW Web Service Request and is presented in Fig. 12, (b).

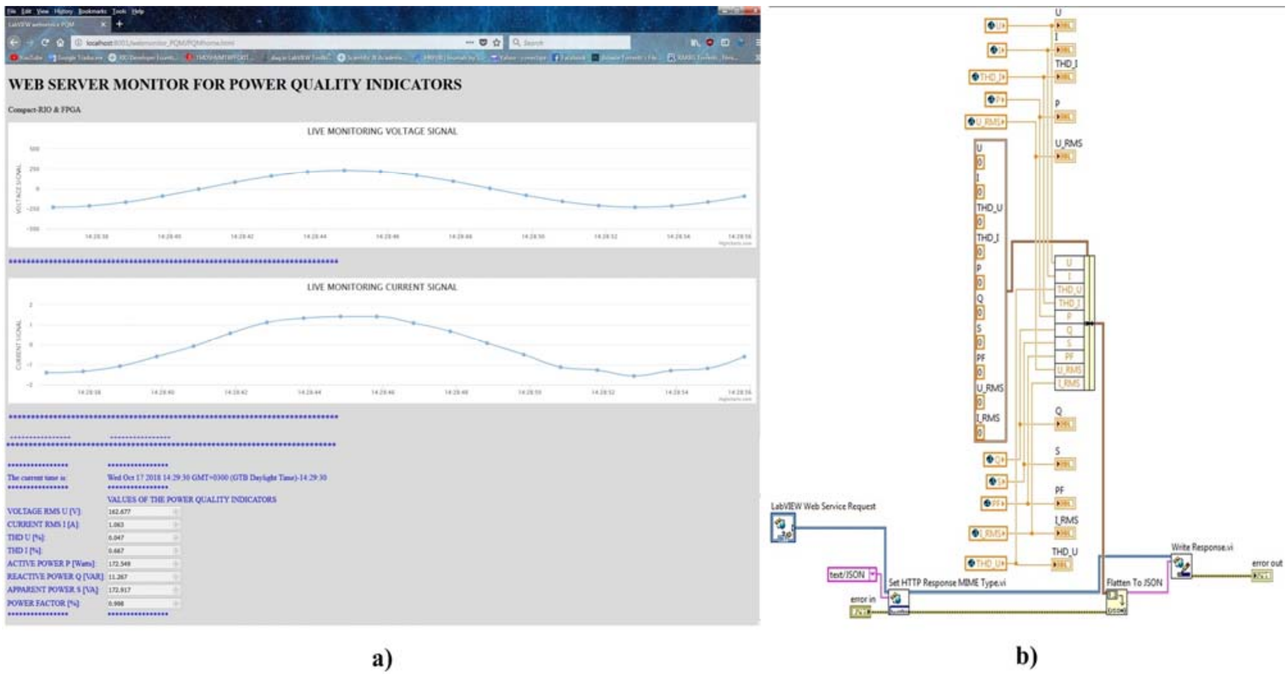

Fig. 12. Disturbance analysis monitoring system – Intranet/Internet integration: (a) PQ parameters Web Browser time evolution, (b) LabVIEW Web-Service request for HTTP Method software block diagram

IV. Practical Experiment

For testing the disturbance analysis monitoring system a practical experiment has been carried out in a laboratory environment whose components are presented in Fig. 13. The computer server and the Host computer implements the software architecture presented in previous section.

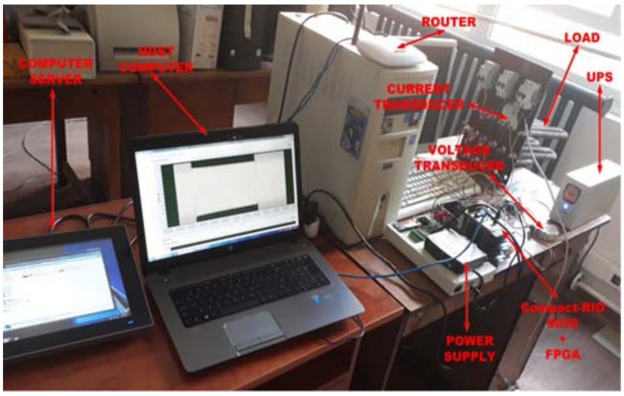

Fig. 13. Image of the practical experiment

The current and the voltage signals are taken from the load, supplied from main network supply through a UPS (Uninterruptible Power Supply), processed by the transducers Hall type acquired through a Compact-RIO-9030 with FPGA in a system with LabVIEW real time capabilities.

Starting with the results from [23-24] where are presented some problems which occur in the network when supplying a consumer from an UPS, in this practical experiment, is analyzed with Wavelet transform means, the phenomenon of coupling and decoupling from a UPS (See Fig. 14).

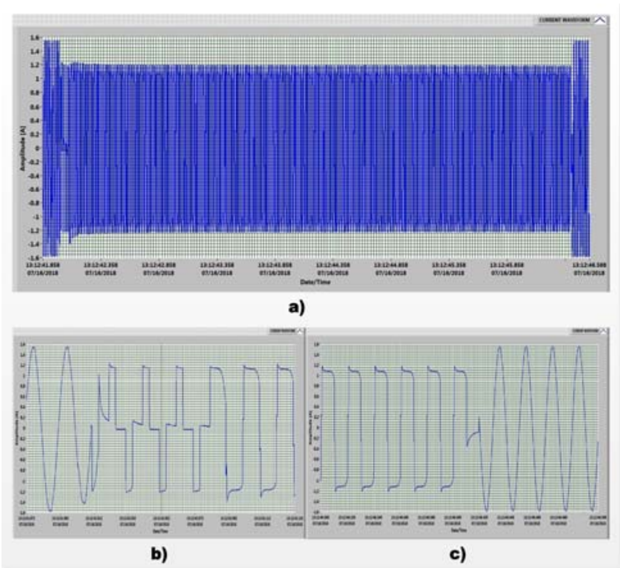

Fig. 14. The acquired current signal: a) At switching between main network supply and capacitors bank of the UPS; b) Detailed of the starting process; c) Detailed of the ending process

The WT analysis of signal by using the Db10 wavelet for current sag harmonics, and the detailed coefficients at nine levels (d1 to d9) and approximation coefficient at level nine (a9) are presented in Fig. 15.

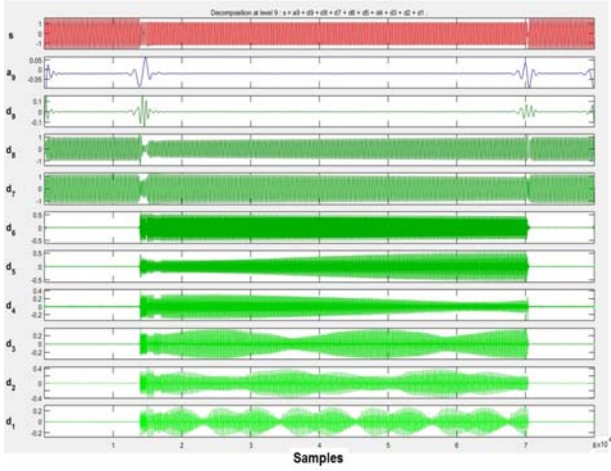

Fig. 15. DWT of current sag with harmonics - detailed coefficients

The waveform graph from the software interface of the current swell disturbance signal is presented in Fig. 16. The WT analysis of signal by using the Db10 wavelet for swell disturbance, and the detailed coefficients at nine levels (d1 to d9) and approximation coefficient at level nine (a9) are presented in Fig. 17.

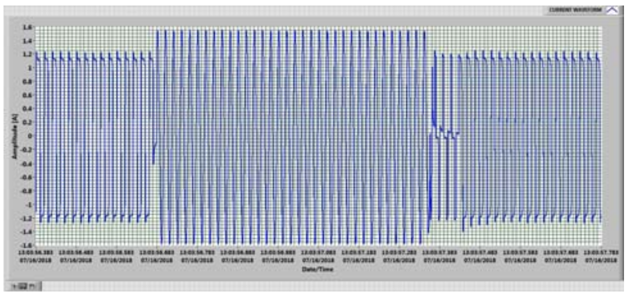

Fig. 16. Current swell disturbance signal

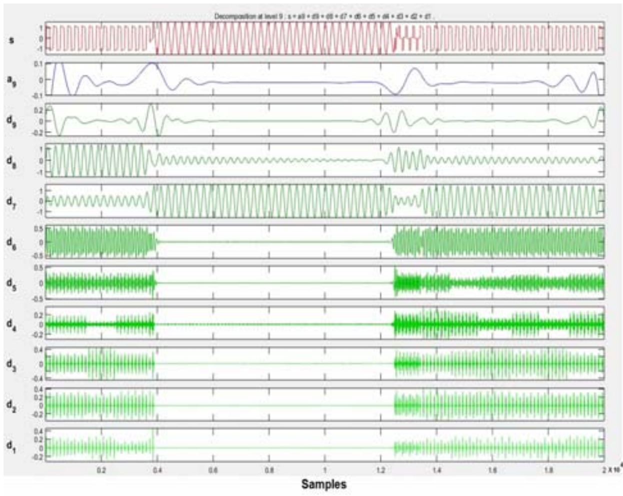

Fig. 17. DWT of current swell - detailed coefficients

For the current interrupt disturbance the waveform graph is presented in Fig. 18. The WT analysis of signal by using the Db10 wavelet for interrupt disturbance, and the detailed coefficients at nine levels (d1 to d9) and approximation coefficient at level nine (a9) are presented in Fig. 19.

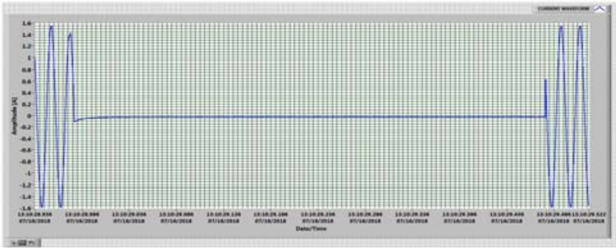

Fig. 18. Current interrupt disturbance signal

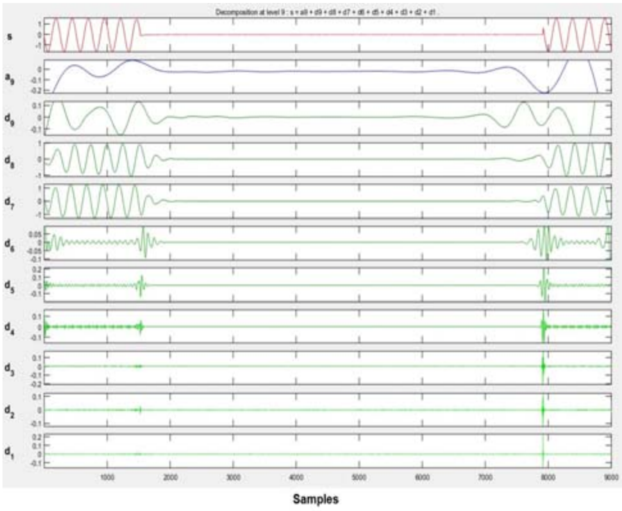

Fig. 19. DWT of current interrupt disturbance - detailed coefficients

V. CONCLUSIONS

This article presents the implementation of a disturbance analysis system, based on LabVIEW Real-Time and reconfigurable FPGA modules using Wavelet Transform.

The presented disturbance analysis monitoring system contains a pre-filtering module for removal of spikes, achieves the storage of entries as TDMS files and Word/Excel type automatic reports automatically sent by email at predefined addresses, contains an OPC UA type server for communication with a hierarchically superior SCADA type system, performs selective entry of the characteristic parameters into a database, contains a Web Server for Intranet/Internet access, for viewing the measured data, and for system management from anywhere, the application is connected to a Cloud-type platform. The main Module is the Wavelet Filtering and Analysis and allows the detection of the characteristic phenomena of the PQ with Wavelet analysis.

The disturbance analysis monitoring system was tested with simulated signals but even in a practical experiment. The future researches will concern on the automatic classifications of the PQ events and on the software optimization.

ACKNOWLEDGMENT

The paper was developed with funds from the Ministry of Scientific Research as part of the NUCLEU Program: PN 18 25 02 03.

Contribution of authors:

First author – 40%

First coauthor – 30%

Second coauthor – 10%

Third coauthor – 10%

Fourth coauthor – 10%

Received on November 9, 2018

Editorial Approval on December 03, 2018

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