An Educational Wavelet-Based Interactive Simulation for Analysis of Power Transients and Short-Time Disturbances.

Radian G. Belu[1], Cosmin Oancea[2], Alexandru R. Belu[3], and Lucian Cioca[4]

1) College of Engineering, Wayne State University, Detroit, Michigan / 2) Department of Computer Science and / 3) Department of Electrical and Computer Engineering, The University of Western Ontario, London, Ontario, Canada / 4) Faculty of Engineering, The University "Lucian Blaga", Sibiu, Romania.

1 Introduction.

In recent years concerns over the quality of electric power has been increasing rapidly as poor electric power quality causes many problems for the affected loads, such as malfunctions, instabilities, short life time and so on. A power quality problem can best be described as any variation in the electrical power service, such as voltage dips and fluctuations, momentary interruptions, harmonics and transients, resulting in mis-operation or failure of end-use equipment. The afore-mentioned disturbances degrade the reliability and quality of power supply. Though they have always existed in utility systems, they are nowadays causing more and more trouble then before. This is due to the increased refinement of today's automated equipment, such as variable-speed drives or robots, automated production lines or machine tools, programmable logic controllers or power supplies in computers. They are far more vulnerable to disturbances on the utility system than the previous generation of electro-mechanical equipment and previous less automated production and information systems [1-3]. The electric power system is full of transient and short-term disturbance phenomena. Such phenomena include lightning transients, transformer in-rush currents, capacitor and line switching transients, motor starting currents, and commutation failure of converter circuits, and these are just a few of the typical power system transients that power engineers would like to efficiently analyze and understand in details.

For these reasons the need of electric power quality monitoring and analysis for both customers and electrical utilities is strongly increased[4,17,15]. This rises the necessity for students to be accustomed with power quality analysis and techniques. Practical experiments in power quality are expensive and difficult to realize while computer simulations are an attractive and less expensive alternative, easy to implement, upgrade and modify. During such simulations the students can try out real processes using material they learn during the class[7]. Wavelet analysis was used in recent years as a new tool for monitoring power quality problems. In the power quality area, most of the work done deals with this problem either from the detection, classification and localization view or from the data compression frames. All the proposed approaches[5,8,12,13] present the localization properties of the wavelet transform. We propose to utilize the dyadic-orthonormal wavelet transform analysis provided by the MATLAB toolboxes to develop and implement a set of computer simulations designed to be used as a teaching aid in the learning process of power quality analysis and monitoring. Wavelet theory provides a unified framework for signal processing applications. In contrast to those Fourier transform based approaches where a constant window size is used for spreaded frequencies the wavelet uses short windows at high frequencies and long windows at low frequencies. By this way, the characteristics of non-stationary disturbances can be more closely monitored[16,5,6]. The transient behavior, cavities and discontinuities in the signals can all be investigated. For example, if an instantaneous impulse disturbance happens to appear at a certain time interval, it may contribute to the Fourier transform but its location on the time axis will be lost. However, by wavelets, both time and frequency information can be obtained[10,5,6]. In other words, the wavelet transforms are much more local. Instead of transforming a pure *time description* into a pure *frequency description*, the wavelet transforms find a good promise - *a time-frequency description.*

The paper is organized as follows. In section 2 we present a general introduction to wavelet analysis. Applications of wavelet analysis for identifying, classifying and analyzing power system disturbances are presented in section 3. Details about user interface, implementation and tests are also included in this section. Finally a conclusion is presented in section 4. The references are included at very end of this paper.

2 Wavelet Transform Analysis - Theoretical Background.

Informally, a wavelet is a short-term duration wave (*ondelette in french*). These functions have been proposed in connection with the analysis of signals - primarily *transients* - in wide range of applications. The wavelet transform is a mathematical tool, much like a Fourier transform in analyzing stationary signals, that decomposes a signal into different scales with different levels of resolution by dilating a single prototype function. The decomposition into scales is made possible by the fact that the wavelet transform is based on a square-integrable function and group theory representation. Furthermore, unlike the Fourier transform which give a global representation of a signal, the wavelet transform, on the other hand, provides a local representation (in both time and frequency) of a given signal; therefore, it is suitable for analyzing a signal where time-frequency representation is needed, such as power quality analysis, short-term disturbances analysis and classification, etc. Wavelets provide greater resolution in time for high frequency components of a signal and greater resolution in frequency for the low frequency components of a signal. In a sense, wavelets have a window that automatically adjusts to give the appropriate resolution. The basic concept of wavelet analysis is the use of a wavelet as a kernel function in integral transforms and in series expansions much like the sinusoid is used in Fourier analysis or the Walsh functions in Walsh analysis (see for details[9,11,14]. The wavelet transform can be seen as a correlation between the signal and the wavelets. But unlike Fourier analysis which uses one basis function, wavelet analysis relies on wavelets of a rather wide functional form. Each wavelet, also called *daughter wavelet* is generated by scaling and translating one original wavelet (basis wavelet), called *mother wavelet.* Scaling implies that mother wavelet is either dilated or compressed and translation implies shifting of the mother wavelet in time domain. We are giving bellow an informal set of conditions that characterizes a wavelet. For a function to be a wavelet the function:

- must be oscillatory,
- must decay quickly to zero (can only be non-zero for a short-period of the wavelet function)
- must integrate to zero (i.e., the dc frequency component is zero).

There are two typical implementations of the wavelet transform: (1) *Continuous Wavelet Transform (CWT)* and (2) *Discrete Time Wavelet Transform (DTWT).*

Let $x(t)$ be a signal defined in $L^2(\Re)$ space, which denotes a vector space for finite energy signals. $\Re$ is a real continuous number system. Such signals satisfy

$$\int_{-\infty}^{\infty} |x(t)|^2 < \infty \tag{1}$$

The wavelet transform of $x(t)$ is then defined as

$$CWT_{\psi}x(a,b) = W_a(a,b) = \int_{-\infty}^{\infty} x(t)\psi^*_{a,b}(t)dt \tag{2}$$

where

$$\psi_{a,b}(t) = \frac{1}{\sqrt{a}}\psi\left(\frac{t-b}{a}\right) \tag{3}$$

$\psi(t)$ is the base function or mother wavelet, the asterisk denotes a complex conjugate, and $a, b \in \Re$, $a \neq 0$. are the dilatation and translation parameters, respectively. It should be pointed out that only functions that have a zero net area can be used as mother wavelet. This suggests that the transformation kernel of the wavelet transform is a compactly supported function (localized in time, as we already pointed out in the previous paragraphs of this section), thereby offering potential to capture power quality disturbance transitions which normally occur in a short period of time.

Since the transformation is achieved by dilating and translating the mother wavelet continuously over $\Re$, it generates substantial redundant information. Therefore, instead of continuous dilation and translation, the mother wavelet may be dilated and translated discretely by selecting $a = a_0^m$ and $b = nb_0a_0^m$, where a_0 and b_0 are fixed constants with $a_0 > 1$ and $b_0 > 0$, $m, n \in Z$, and Z is the set of positive integers. Then, the discrete mother wavelet becomes

$$\psi_{m,n}(t) = a_0^{-m/2}\psi\left\{\frac{t - nb_0a_0^m}{a_0^m}\right\} \tag{4}$$

and the corresponding discrete wavelet transform is given by

$$DWT_{\psi}x(m,n) = \int_{-\infty}^{\infty} x(t)\psi_{m,n}^{*}(t)dt \tag{5}$$

where $\psi_{m,n}(t)$ is given in (4).

By careful selection of a_0 and b_0, the family of dilated mother wavelets constitutes an orthonormal basis of $L^2(\Re)$. The orthonormal basis has two main implications. The first is that there is no information redundancy between the decomposed signals. The second refers to the existence of an elegant algorithm, known as the multi-resolution signal decomposition technique, that decomposes a signal into scales with different time and frequency resolutions (for a fixed choice of a_0 and b_0). As we mentioned earlier the choice of the mother wavelet plays a significant role in detecting and localizing various types of power quality disturbances. The selection of an appropriate mother wavelet without knowing the transient disturbance's type can be a daunting task. We decided to use Daubechies wavelets in our simulation(11), and we will use only one type of mother wavelet in the whole course of detection and localization for all types of disturbances.

3 Implementation, Simulation and Results.

A power quality problem, as we discussed earlier, represents any disturbance manifested in voltage, current or frequency deviation that may result in failure or misoperation of electric equipment. As we already pointed out we developed a computer simulation applications, based on the MATLAB tool-boxes, in order to allow the students to study, identify and classify the short-term power disturbances.

The proposed simulation laboratory application will provide hands-on experience of power quality analysis for students. The proposed laboratory simulation software, as listed below, will serve both educational and research activities (for students interested in doing their final senior project in power quality analysis). **Laboratory Structure:** The simulation

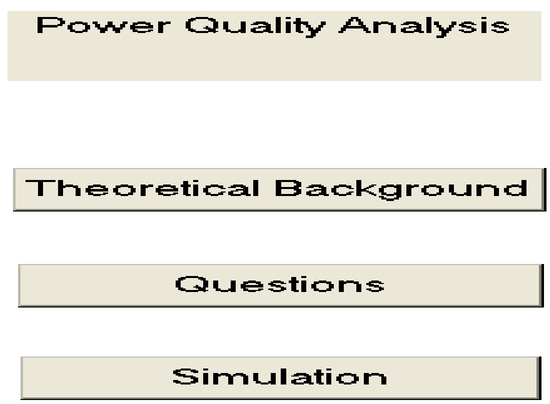

Figure 1: Main Menu.

laboratory will be designed as an independent educational module, which will be composed of the following parts:

Theoretical background: Providing to the students the theory to prepare the experiments and simulation. Feedback on learning process: questions are placed at the end of theoretical section to provide feedback to student on the quality of his/her learning. In response to the results hints are given for complementary studies.

Experiments and simulations. A set of simulated experiments will complete the application. Another set of questions will be required to be answered at the end of this section, after the final mark, for this unit will be assigned to each students. The students are allowed to perform the experiments and simulations only after answering correctly to most of the questions from section 2 of the simulation. The test questions will be appropriately selected, to cover the theoretical aspects that lay the foundation for a specific experiment in the unit, and therefor are requested to be known by the student.

Laboratory Work and Evaluation. The number of students enrolled in the electric machines and power systems course is normally over fifteen. Students will be grouped into three-to-four member teams, to perform one laboratory module. This numbers have been chosen because they are large enough to be considered a team, and small enough to be easily managed from an educational point of view. Students can freely compose these teams. A multi-disciplinary team can enroll members that have different skills. Once teams are made up, the documentation of each laboratory module will be passed, well in advance to each team. This documentation package will include the topics listed above. Students will also receive a complete laboratory schedule. The student work will be organized around the phases listed above. For each phase some outputs should be produced. Evaluation will be based on the documentation rendered by the students at the end of the session. Each team works individually. At the end the session the whole process will be discussed with the students, and the final grade will be assigned. The performance of the laboratory and the submission of the reports, not only for this unit, but for the entire laboratory is a prerequisite for entry to exams. The report for each laboratory experiment, including power quality analysis one are due in two weeks after it was performed. At the specified day and time, the students come to the laboratory, perform the experiment, and store all the relevant results of the experiment (computer simulations, answers to the questions, etc) on a personal floppy disk.

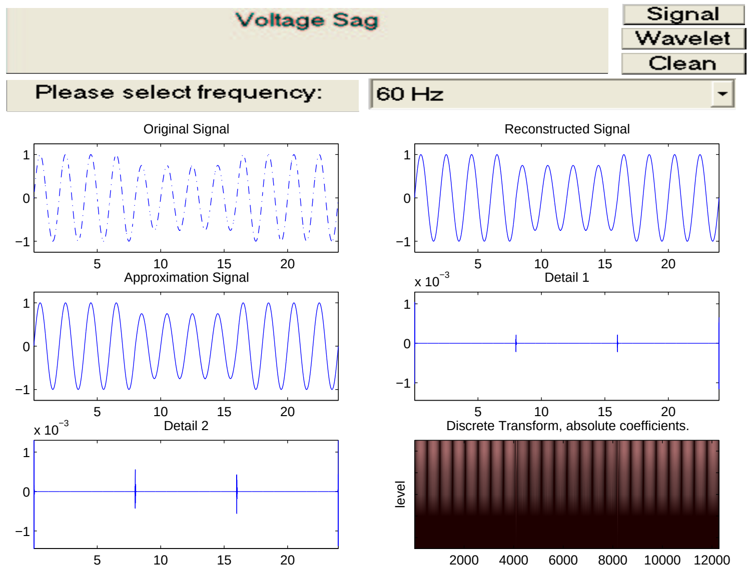

Figure 2: Voltage Sag.

3.1 Implementation and Results.

A friendly user interface was designed to allow the students to use software simulation for power quality analysis. Figure 1 shows the main menu, which consists of three choices: (1) theoretical background; (2) questions; and (3) simulations. As we mention earlier, after the students fulfill section *(2) questions* they are allowed to use section *(3) simulations*. In this section they have the possibility to select different types of transients and short-term power disturbances, such as transient impulses, voltage sag, voltage interruption, voltage harmonics, etc.. The interface is also developed in MATLAB. The students can select the parameters of the voltage signals, such as amplitude, frequency, etc. The disturbances and transients are generated by a set of subroutines and are superimposed randomly over signals. Figures 2 to 4 show three different disturbances and their perfect localization and some of their features. As we mentioned earlier the main advantage of wavelet-based method comes from its ability to separate power quality problems that overlap both in time and frequency. Figures 2 to 4 demonstrate that we are able to separate the pure signal from any high or low frequency content, dc content, or noise distortion. We consider this to be a very useful experiment of electric power system. Another advantage of our method is to expose the engineering students to a new technique, wavelet analysis, very powerful in signal analysis and processing. Feedback, especially from students will help us to improve our simulation package,

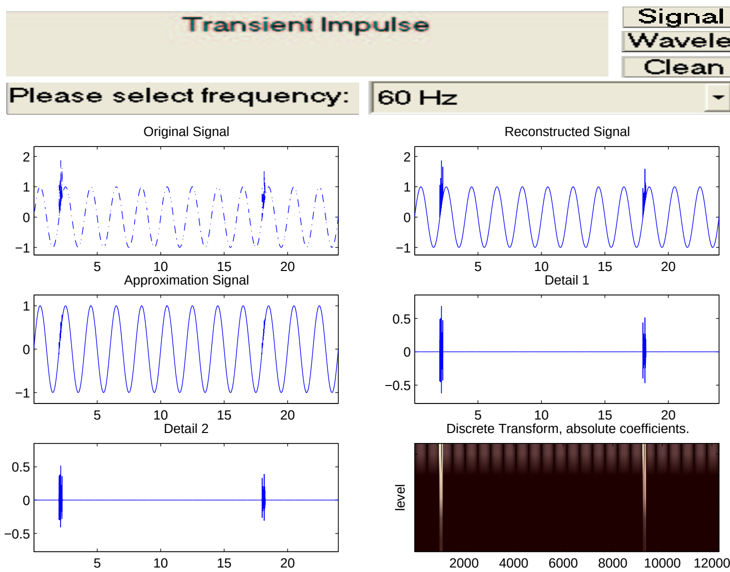

Figure 3: Transient Impulses.

both in terms of interface and experiments. It is our intention to extend the framework to include automated feature extraction and analysis, in a manner similar to the approaches find in the literature[5,8,17]. Parts of upgraded version and new features of our power quality analysis simulation package will be developed by the students as part of their senior and/or undergraduate research projects in our division.

4 Conclusions and Discussions.

The paper has presented a new method for quality analysis in electrical power systems, based on the wavelet analysis approach. A wavelet transform approach was applied to develop software applications, used as a teaching aid in the Electric Machines and Power Systems course. The simulation is designed to facilitate the learning of power quality analysis, short-term disturbances identification, classification and characterization. From the testing results, we have demonstrated that the proposed approach was very successful in detecting and localizing different kinds of power system disturbances. A friendly user interface was designed and implemented, in order to allow the students to select, classify and identify power system disturbances, and test their knowledge on the subject. The authors intend to improve this MATLAB simulation, by taking into account the students' feedback (collected by means of a survey, performed during the class).

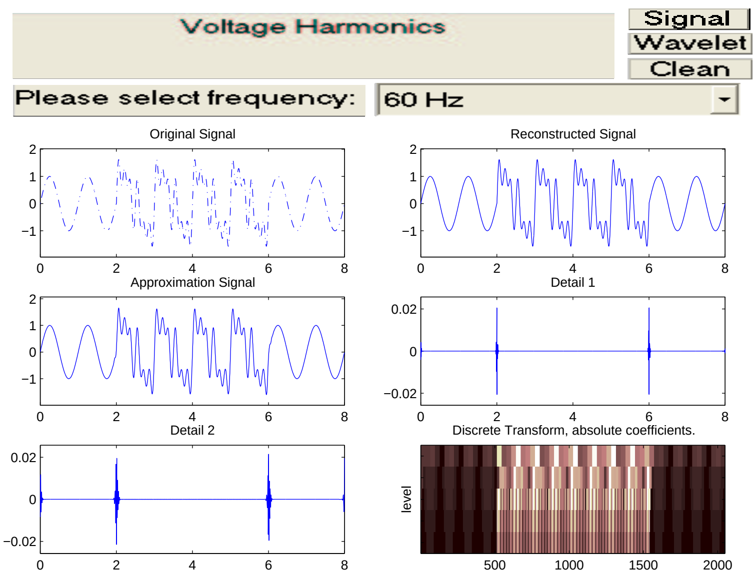

Figure 4: Voltage Harmonics.

Acknowledgments: I would like to thank Maria Belu for carefully reading and correcting the manuscript of this paper.

References

[1] Sabin D.D. and A. Sundaran, "Quality enhance relaiability", IEEE Spectrum, Vol. 33, Feb. 1996 pp. 34-41.

[2] Dabbs W.W., D.D. Sabin, T.E. Grebe, and H. Mehta, "Probing Power Quality Data ", IEEE Comp. Appl. in Power, April 1994, pp. 8-14.

[3] Heydt G.T., *Electric power quality*, Indianapolis, Indiana, USA, Stars in a Circle Publications, 1991.

[4] Angrisani L, P. Daponte, M. D'Apuzzo, and A. Testa, "A measurement method based on the wavelet transform for power quality analysis", IEEE Trans. on Power Delivery, Vol. 13, Oct. 1998, pp. 990-999.

[5] Angrisani L, P. Daponte, M. D'Apuzzo, "A method for the automatic detection and measurement of transients. Part I: the measurement method ", Measurement, Vol. 25, 1999, pp. 19-30.

[6] Agrisani L., P. Duponte, and M. D'Apuzzo. "A method for the automatic detection and measurements of transients. Part II: applications", Measurement, Vol. 25, 1999, pp. 31-40.

[7] Bose T., "A Digital Signal Processing Laboratory for Undergraduate ", IEEE Trans. on Edu., vol. 37, Aug 1994, pp. 243 - 247

[8] Gaouda A.M., M.M.A. Salama, M.R. Sultan, and A.Y. Chikhani, "Application of Multiresolution Signal Decomposition for Monitoring Short-Duration variations in Distribution Systems ", IEEE Trans. on Power Delivery, Vol. 15, April 2000, pp. 478-486.

[9] Heil C.E., and D.F Walnut, "Continuous and Discrete Wavelet Transforms ", SIAM Review, Vol. 31, No. 4, Dec. 1989, pp. 628-666.

[10] Huang S., C. Hsieh, and C. Huang, "Application of Morlet Wavelets to Supervise Power System Distrubances ", IEEE Trans. on Power Delivery, Vol. 14, Jan. 1999, pp. 235-244.

[11] Daubechies I., "The Wavelet Transform, Time-frequency Localization and Signal Analysis ", IEEE Trans. Inf. Theory, Vol. 36, No. 5, 1990, pp. 961-1005.

[12] Littler T.B. and D.J. Morrow, " Wavelets for the Analysis and Compression of Power System Disturbances ", IEEE Trans. on Power Delivery, Vol. 14, April 1999, pp. 358-365.

[13] Poisson O., P. Rioul, and M. Meunier, "New Signal Tools Applied to Power Quality Analysis ", IEEE Trans. on Power Delivery, Vol. 14, April 1999, pp. 561-567.

[14] Williams J.R., and K. Amaratunga, "Introduction to wavelets in Engineering ", Int. J. for Numerical Methods in Eng., Vol. 37, 1994, pp. 2365-2388.

[15] Pillay P. and A. Bhattacharje, "Application of wavelets to model short-term power system disturbances ". IEEE Trans. on Power Systems, Vol. 11, Nov. 1996, pp. 2031-2038.

[16] Rioul O., and M. Vetterli, "Wavelet and Signal Processing ", IEEE Signal Processing Magazine, Vol. 8, October 1991, pp. 14-38.

[17] Santoso S, E.J. Powers, W. Mack Grady, and P. Hofmann, "Power Quality Assessment via Wavelet Transform Analysis ", IEEE Trans. on Power Delivery, Vol. 11, April 1996, pp. 924-930.

Radian G. Belu was born in Teleorman, Romania. He hold a PhD in Electrical Engineering and other in Physics. He published over 40 papers and conference presentations in fields of Radar,

Remote Sensing, Telecommunications, Lightning Electrodynamics, Power Engineering and Physics. He is currently Assistant Professor at College of Engineering, Wayne State University, Detroit.

Cosmin Oancea was born in Bucharest, Romania, He hold a M.Sc. in Computer Science and Engineering from M.Sc. Department of Electric Engineering and Computer Science, "Politehnica" University of Bucharest. Romania He is currently Ph.D. graduate student at Department of Computer Science, University of Western Ontario, London, Canada

Alexandru Belu was born in Alexandria, Romania. He hold a B.Sc. Degree in Electrical Engineering from Department of Electrical and Computer Engineering, The University of Western Ontario, Canada. He is currently M.Sc. graduate student in Software Engineering, Department of Electrical and Computer Engineering, The University of Western Ontario, Canada.

Lucian Cioca hold a PhD in Industrial Engineering from University of Petrosani, Romania. He is currently Lecturer in Engineering Management at Faculty of Engineering, University "Lucian Blaga", Sibiu, Romania.