Simulation of Power Quality Disturbances through the Wavelet Transform

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Abstract— **Most of the related PQ disturbances studies are addressed exclusively through standing advanced mathematical concepts without possibility to test these techniques over synthetic signals. This paper presents a new application implemented in MATLAB that has been developed to set up different synthetic signals, PQ disturbances and white noise. Afterwards, FT, STFT, CWT, DWT and denoised signals are calculated. Moreover, the application can connect to any device via RESTful web service and query for data stored in smart sensors. The novelty of this application lies in the fact that it allows to monitor FT, STFT, CWT, DWT and the denoised signals continuously.**

Index Terms-- **Continuous Wavelet transform, Discrete Wavelet transform, MATLAB, Power Quality, Signal analysis.**

I. INTRODUCTION

Good power quality refers to disturbance-free electricity supply. With the development of technology, more and more electronic devices are being connected to the grid, causing potential disturbance and deviation from the supplied voltage sinusoidal waveform, which may result in equipment being disturbed or damaged. Having in mind that power quality (PQ) disturbances are sources of voltage disturbances, which degrade and might damage modern devices [1], power electronic devices haven been lately developed considering PQ issues [2]. Furthermore, power quality is an important aspect to consider for renewable energy integration. For example, current harmonics produced by power converters are limited to guarantee power quality in renewable energy systems.

PQ disturbances such as swell, sag, interruption, oscillatory transients, flicker and harmonic distortion are becoming challenging issues for power systems analyses. The modulated power sinusoids are also detected when there are changes in loads and varying energy sources [3]. All these issues may impose penalties to the consumers by adding reactive power, re-dispatch cost and load curtailment cost.

To understand PQ disturbances, the time-frequency features of these signals should be detected and analyzed [4,5]. Fourier transform (FT) is one of the most used technique in the frequency domain, along with Short Time Fourier Transform (STFT) [6] that allow to perform windowing techniques. FT calculations are widely implemented with broad applicability, but some disadvantage are present because of it is difficult to balance the frequency resolution using STFT. The signals must be stationary in both amplitude and frequency. Otherwise, the analysis results will be not acceptable.

Advanced frequency techniques have also been developed. For example, Hilbert Huang transform (HHT), Stockwell transform (S-transform) and Wavelet transform (WT) [7,8]. S-transform is a hybrid of STFT and WT with variable window. WT can accurately detect a single event in non-stationary conditions when the PQ disturbance occurs. WT has suitable frequency, focusing characteristics, resolution and it can deal with some acceptable level of noise [9].

To set up the WT, different approaches should be considered. The Continuous Wavelet transform (CWT) analyses the signal translating over the time for different scaling factors. The Discrete Wavelet transform (DWT) can be used to make a multiresolution analysis, which is used to decompose a discretized signal into different resolution signal levels [9,10].

The literature review reveals that most of the related studies are addressed exclusively through standing advanced mathematical concepts without possibility to test these techniques over synthetic signals. Herein, a MATLAB graphical user interface (GUI) application has been developed to cover this gap. In this GUI application, the user can set various synthetic signals with different PQ disturbances and white noise controlled by the user. Afterwards, the FT, STFT, CWT, DWT can be calculated and the signal is denoised. Other interesting feature of this application is that the user can modify the parameters and compare the results obtained. Moreover, the application can connect to any device via RESTful web service and query for data stored in smart sensors. The data are treated as JSON. Therefore, monitoring FT, STFT, CWT, DWT and the denoised signal for each short span time is possible. The span time is controlled by an interruption released by a timer, which was integrated in the MATLAB code. The span time is configured by default.

II. POWER SYSTEM DISTURBANCES

Magnitude and duration are the two variables that are considered to categorize PQ disturbances. We can classify them as two different phenomena: steady-state and transient. Sag distortion, voltage flickers, oscillatory transient, swell and outage can be classified into steady-state or transient.

Table 1. PQ disturbances considered in this GUI application.

Symbol	PQ disturbance	Equation	Parameters
PQd1	Sag	$y(t) = (1 - \alpha(u(t - t_1) - u(t - t_2))\sin(wt)$	$0.1 \leq \alpha \leq 0.9, T \leq t_2 - t_1 \leq 9T,$ $t_1 \leq t_2$
PQd2	Swell	$y(t) = (1 + \alpha(u(t - t_1) - u(t - t_2))\sin(wt)$	$0.1 \leq \alpha \leq 0.8, T \leq t_2 - t_1 \leq 9T,$ $u(t) = \begin{cases} 1 \; t \geq 0 \\ 0 \; t < 0 \end{cases}$
PQd3	Interruption	$y(t) = (1 - \alpha(u(t - t_1) - u(t - t_2))\sin(wt)$	$0.9 \leq \alpha \leq 1, T \leq t_2 - t_1 \leq 9T$
PQd4	Flicker	$y(t) = (1 + \alpha_f \sin(\beta wt))\sin(wt)$	$0.1 \leq \alpha_f \leq 0.2, 5Hz \leq \beta \leq 20Hz$
PQd5	Oscillatory transient	$y(t) = \sin(wt) + \alpha\, e^{-(t-t_1)/\tau}\sin(w_n)$ $(t - t_1)(u(t_2) - u(t_1))$	$0.1 \leq \alpha \leq 0.8, 0.5T \leq t_2 - t_1 \leq 3T,$ $8ms \leq \tau \leq 40ms, 300 \leq f_n \leq 900$
PQd6	Harmonic	$y(t) = \alpha_1 \sin(wt) + \alpha_3 \sin(3wt)$ $\alpha_5 \sin(5wt) + \alpha_7 \sin(7wt)$	$0.05 \leq \alpha_3 \leq 0.15, 0.05 \leq \alpha_5 \leq 0.15$ $0.05 \leq \alpha_7 \leq 0.15, \sum \alpha_i^2 = 1$

However, all these variations of voltage have different characteristics. In order to deal with these differences, it is necessary to develop new methods capable of detecting and classifying these PQ disturbances [11-12]. PQ disturbances definitions are stated in standards IEEE 1159 [13], IEC61000-4-30 [14] and EN50160 [14].

Table 1 shows the PQ disturbances considered for the GUI application, where the parameters are randomly determined applying the given inequation. These disturbances were selected for its mathematical simplicity and the ease in the implementation of the GUI application.

III. WAVELET TRANSFORM

Wavelet transform (WT) is a mathematical technique widely used in signal processing theory. WT is a powerful tool compared with conventional methods in processing stochastic signals. In WT, the high and low frequencies are windowed applying a scaling factor. This is a method for advanced time-frequency analysis. The application of WT is very wide, including neurocomputing [15], EGG, denoising signal and filtering and image compression [16]. Also, WT has successfully been applied by many pattern recognition algorithms and is a useful method for power quality researchers. The Continuous Wavelet transform of a signal *f(t)* can be mathematically represented by

$$CWT_\psi f(a,b) = \int_{-\infty}^{+\infty} f(t)\psi_{a,b}(t)dt \qquad (1)$$

where

$$\psi_{a,b}(t) = |a|^{-\frac{1}{2}}\psi\left(\frac{t - b}{a}\right) \qquad (2)$$

As example, Figure 1, shows a current signal read from a power network analyzer in a real scenario. The Continuous Wavelet Transform of that signal is displayed in Figure 2.

The Continuous Wavelet Transform give us information about the instant frequency for each instant time. Therefore, disturbances affecting the instant frequency can be detected.
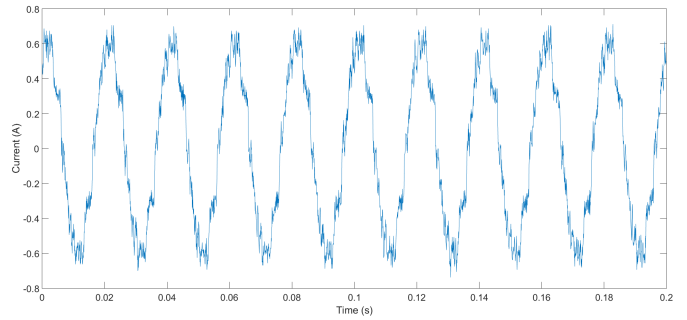

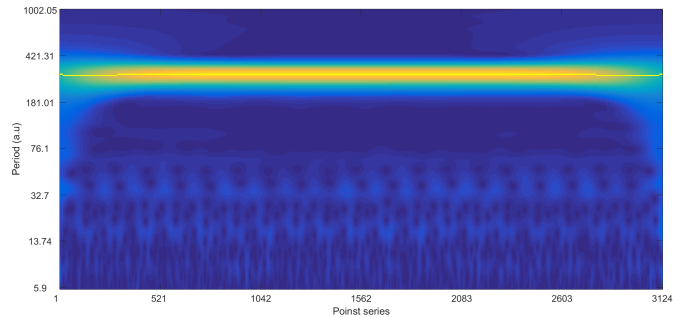Figure 1. Real current signal read from a power network analyzer.

Figure 2. Continuous Wavelet Transform of the real current signal read from a power network analyzer.

The Discrete Wavelet transform (DWT) of *f(t)* can be defined as:

$$DWT_\psi f(m,n) = \int_{-\infty}^{+\infty} f(t)\psi_{m,n}(t)dt \qquad (3)$$

Where ψ is the mother wavelet. The discrete wavelet transform is used to compose the multi-resolution analysis (MRA). In general terms, the MRA represents the signal at

different resolutions after applying two filters in each level: a low pass filter (LPF) and a high pass filter (HPF) [17]. The MRA set an orthogonal scaling function $\phi(t)$ and Wavelet function $\psi(t)$ which divide the space into a series of orthogonal high frequency and low frequency spaces.

The discrete wavelet transform of the real current signal is shown in Figure 3. Note that this DWT shows the decomposition of the signal in different band levels. The decomposition obtained can give us valuable information about the power quality and his influence due to disturbances. These disturbances introduce artifacts into the signal.
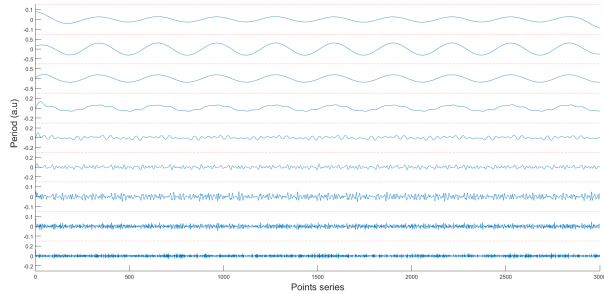

Figure 3. Discrete Wavelet Transform of the real current signal. The discrete wavelet transform is used to compose the multi-resolution analysis.

The GUI application has implemented CWT using several mother wavelet functions: Morlet, Paul, and Derivative of Gaussian (DOG). In the other hand, DWT application has been implemented using Daubechies, Haar and Mexican Hat mother wavelets. As an example, the Morlet Wavelet mother function can be expressed as:

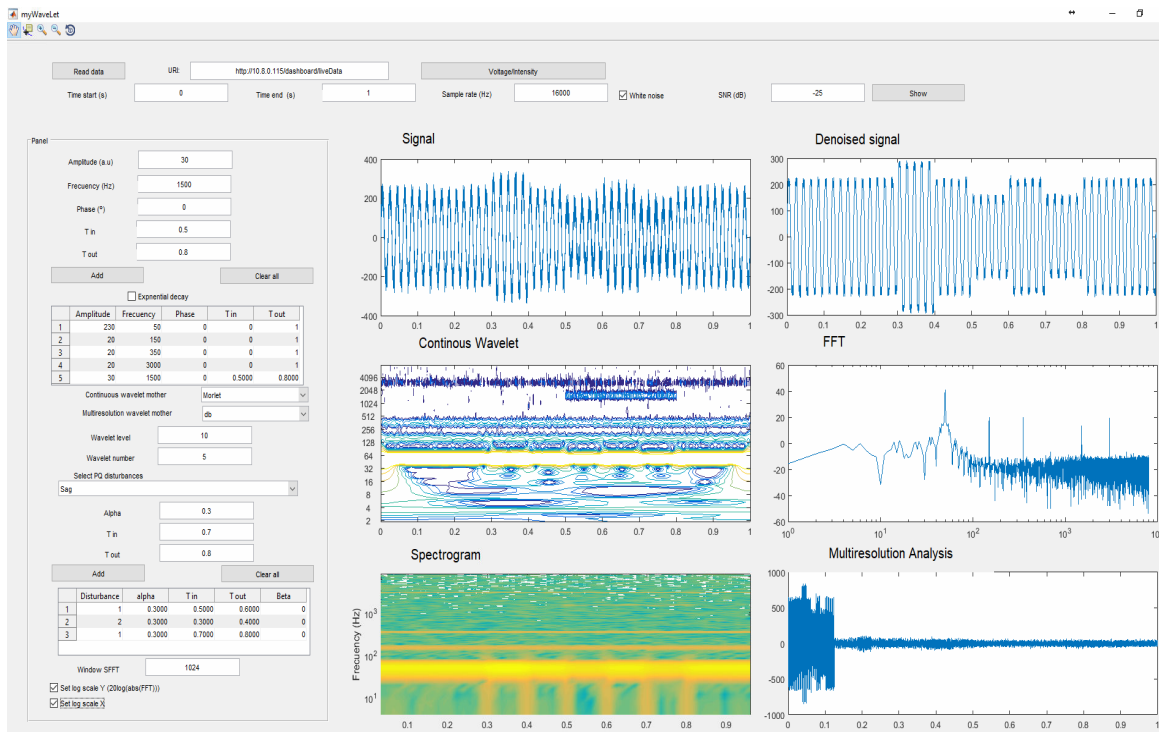$$\psi(t) = e^{-\frac{\beta t^2}{2}} e^{-j\omega_o t} \qquad (4)$$

IV. MATLAB APPLICATION

Figure 4 shows the overall view of the application. In the top view, main parameters like start and stop time of the signal can be set. The user can plot a synthetic signal or real one, the CWT, the DWT via MRA, the STFT, the FT and, finally, the denoised signal. In addition, a RESTful web service is implemented and can be connected to any external device for data acquisition. In the left side of the application, parameters signals, PQ disturbances and some other parameters are set up for the calculations. The main parameters are:

- *Amplitude*: the amplitude of the signal. To simulate the main signal, the user can set the amplitude, thus simulating any real value of a power system. Also, it is possible to add another signal as harmonic with different amplitude and order of the main frequency.

- *Frequency*: the frequency of the signal. To simulate harmonics, it is possible to modify the frequencies. Figure 1 shows four harmonics at 150 Hz, 350 Hz, 1500 Hz and 1500 Hz.

- *Phase*: it is possible to add a custom phase value between different signals. In our test case, the phase was set to 0 for all signals.

- *Time in*: to simulate more realistic scenarios, harmonics can be entered at a certain time instant.

- *Time out*: The harmonics sometimes disappear at a certain time. The application allows this option.

Figure 4. A general view of the GUI application.

To set up the calculations, it is necessary to establish the type of the mother Wavelet function used by CWT and DWT. The CWT and DWT have different mother functions. For CWT, Morlet, Paul and DOG mother wavelet functions are widely used. On the other hand, Daubechies, Haar and Mexican Hat mother wavelet functions are considered for DWT, which also requires to set the values of the Wavelet levels (i.e. the number of iterations in the MRA), and Wavelet number (i.e. the iteration desired for plotting).

The PQ disturbances are also to set up in the left side of the application. All PQ disturbances are described in Table 1 and all parameters can be entered for each PQ disturbance. Several signals can be also entered if necessary. The application allows to set a logarithmic scale for Fourier transform and the value of window for STFT, while the white noise is introduced using a check box that allows to convert the value to decibels (dB). By default, the signal is denoised using DWT.

As Figure 4 shows, the application has six plotting areas. The first plot is used for the synthetic signal with all PQ disturbances, harmonics and white noise. The second plot is used for synthetic signal denoising. In the third plot, the continuous Wavelet transform is applied to the synthetic signal previously selected. The mother Wavelet function is Morlet by default. The Fourier transform is plotted in the fourth axes; logarithmic scales are allowed for this plot. A spectrogram is plotted in another area. A STFT is computed using the window parameter to get a spectrogram. The last displayed plot is the multi-resolution analysis (MRA), which is computed using the number of levels as input parameter.

Figure 5 shows a more detailed view of the continuous Wavelet transform applied to the synthetic signal. It is important to notice that it is possible to display a specific level by setting the Wavelet number.

Herein, it is easy to recognize three bands that correspond to the different harmonics contained in the synthetic signal and the main harmonic (yellow contour). Moreover, between 0.5 and 0.8 second a 29th harmonic is applied to the synthetic signal. The Morlet mother wavelet detects this component and clearly delimit the time span.
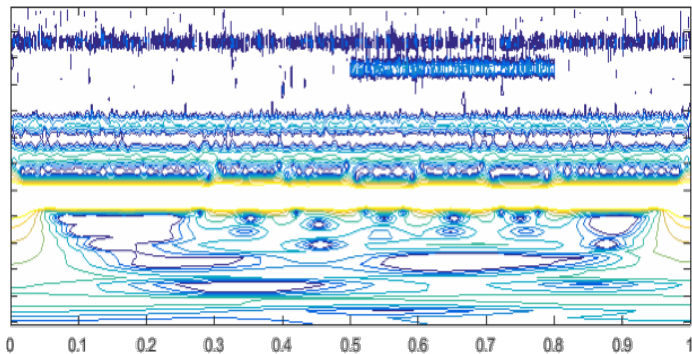

Figure 5. Detailed view of Continuous Wavelet Transform.

Some voltage disturbances are also applied to the main harmonic component (yellow contour). Between 0.3 and 0.4 seconds a Sag perturbation is injected into the synthetic signal.

WT can detect this disturbance by inspecting the width of the band level. Otherwise, a swell is applied to the signal between 0.5 and 0.6 seconds. The band width becomes shorter during this span of time. Finally, a Sag disturbance is applied again and an increase of the band width can be observed too, in the range of 0.6 to 0.7 seconds. Therefore, Figure 5 is very illustrative to determine how the Wavelet Transform works and detects PQ disturbances.

V. RESULTS AND DISCUSSION

A synthetic signal simulation is performed and the graphical results are displayed in Figure 1. It consists of a main signal with 230 V of amplitude and 50 Hz of frequency during all simulation time. The simulation time is set up to 1 second with white noise applied. The gain of the white nose is -25 dB. Harmonics of 150 Hz, 350 Hz, 1500 Hz and 3000 Hz are introduced at different time spans. Morlet and Daubechies mother functions are selected for CWT and DWT, respectively. Some sags, swells and oscillatory transients are also entered as PQ disturbances.

The CWT successfully detects the harmonics, while the spectrogram of STFT cannot detect it. Some artifacts related to the PQ disturbances are plotted in the CWT area. Obviously, the FT and STFT cannot detect all these issues. The MRA detects artifacts in the second and third level.

VI. CONCLUSIONS

All electrical devices are prone to failure when exposed to one or more power quality problems. This paper presents a graphical user interface for simulating Power Quality disturbances of synthetic and real signals using some time-frequency transformations. This application, implemented in MATLAB, is useful for monitoring power signals since it applies advanced transformations. Moreover, the application can connect to any device via RESTful web service and query for stored data in smart sensors.

Herein, the application serves as a preliminary step to analyze and classify these PQ disturbances. Advanced techniques will be incorporated to the application for automatically detecting PQ disturbances in a quantitative manner. Techniques as principal component analysis (PCA) or kernel component analysis (KCA), neural network for classification (CNN) and support vector machines (SVM) will be considered. Also, boundaries decision will be investigated to react adequately for all these power quality issues.

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