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Visualization of Quality Performance Parameters Using Wavelet Scalograms Images for Power Systems

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Abstract:
Power quality problems are not new to power systems, but they cannot be overlooked. In the context of Smart Grids, power systems are undergoing a transformation characterized by the high penetration of renewable sources and electronic devices in the grids, in addition to greater computerization of operations. Thus, alternatives in the representation and visualization of these integrated quality parameters become more and more necessary, both for a better understanding of these phenomena and for advanced applications with the use of images. With this in mind, this paper aims to present an alternative for visualizing PQ disturbances through 2-D images from scalograms based on the continuous wavelet transform (CWT) and multiresolution analysis. For this, signals from three different sources, mathematical equations, models of transmission and distribution of energy in MATLAB / Simulink, and real signals from a database were used. For the creation of the scalogram images, the signal processing technique, and the use of a color map were used to show the performance. The results showed the efficiency of the method for visualization and characterization of addressed disturbances. The enkaptics phenomena were also highlighted, which show the simultaneity and relationship between different types of signal variation. The work contributes to using signals from different sources, synthetic, from simulation or real signals, to offer a methodology that describes tools for a method of visualization.

Keywords: Image Visualization; Power Quality; Scalogram; Signal Processing; Wavelet Transform.

1. INTRODUCTION

In the last decades power quality (PQ) has become a major concern to both power utilities and power consumers as a result of deregulation, the widespread use of sensitive loads, power electronic devices and the complexity of industrial processes (Bollen and Gu, 2006). Electric power systems increasingly demand solutions to the various issues that arise, especially with the growth of the complexity in the electric grid. In this constant transformation characterized by the wide insertion of renewable sources and the modernization/computerization of systems, the PQ problems are also taking on new scopes, even the most well-known events. Proliferation of distributed generation, emphasis on energy efficiency, green power, and the intensification of the use of power electronics with new technologies, including high frequency switching, etc., will demand creative efforts to cope with the current and future developments (Bollen et al., 2010).

PQ is an important aspect of the power system, which cannot be neglected, and an adequate power quality guarantees the necessary compatibility between consumer equipment and the grid (Zavoda et al., 2018). This issues can be addressed as any power problem manifested in voltage, current, or frequency deviations that result in failure or misoperation of customer equipment (Surya Santoso et al., 2012). The identification of these types of events is essential to ensure the smooth operation of the systems. Any change in the 50/60 Hz sine waveform of current or voltage can be a disturbance. Visualization of these events is essential to provide diagnostics that assist in the required procedures.

Events such as voltage sags, capacitor switching transients, short-term faults, voltage swell, among others, are the main causes of disturbances measured in the electrical grid. The identification of these transients can be performed by several methods, both computational and visual inspection of events in the time domain, the latter being more traditional.

Advanced signal processing techniques are great allies to mitigate the effects of these disturbances. These application options generate different opportunities for viewing these events. With the advancement of computerization and image processing, today it is possible to reproduce signals of different shapes and dimensions, using tools that highlight their characteristics.

Wavelet techniques aplied to power engineering fall into two broad, overlapping areas: identification and analysis (Galli et al., 1996). The wavelet transform becomes a powerful tool when it comes to characterizing signals, mainly transient. Through this transformation and multiresolution analysis, it is possible to create images to discriminate quality performances. The ability of the wavelet transform to localize both time and frequency makes it possible to simultaneously determine sharp transitions of the signals and in the localization of their occurrence (Liu and Pillay, 1999).

At a certain point in the past, wavelet transform began to be widely used in the literature, especially in applications of power systems. In (Liu and Pillay, 1999), the use of multiresolution analysis was already highlighted for the identification and representation of quality transient events, in addition to presenting the points where the wavelet works and the Fourier transform fails. The work on (Ribeiro, 1994), on the other hand, had already proposed the use of the wavelet transform as a tool to analyze non-stationary harmonic distortions in power systems. In this sense, Liu et al. (1999) places in their work the wavelet transform and multiresolution analysis as a solution for visualizing transients and electrical power systems. At this point, the work also highlights the potential of scalograms to carry out analyzes of events and the representation of these phenomena. Typical power transients were used. The representations proved to be efficient and characterize the signals. Also using this way of characterizing these signals, Gonzalez et al. (2008) explores the possibilities of Continuous Wavelet Transform (CWT) to power quality (PQ) analysis employing simulation. The signature of different PQ disturbances on the signal scalogram is shown.

In the literature, it is possible to find other works that deal with the visualization of disturbances through alternative and successful forms of visualization. Aung et al. (2004) describes modular software for the automated assessment and visualization of voltage sag performance, it allows in-depth analysis of voltage sag performance of the individual buses, the performance of the entire network at different voltage levels. In (Xu et al., 2006), a comparative study of four techniques of analysis and visualization of distortions in the format of where variants in time is presented. Techniques include fast fourier transform (FFT), shot-time fourier transform (STFT), discrete wavelet transform (DWT) and S-transform. Finally, the advantages and problems of technincas for visualizing these signals are presented.

The purpose presented in (Gomez-Lazaro et al., 2009) is to describe and assess a new characterization and classification method of voltage dips. For visualization purposes, a voltage-space vector representation is introduced to clarify the global voltage dip evolution along the time. Silveira and Ribeiro (2009) demonstrated and encouraged the use of wavelets as an alternative to the inadequate traditional harmonic analysis and still maintain some of the physical interpretation of harmonic distortion viewed from a time-varying perspective. In addition to showing an application with high fidelity signals generated in a real-time simulator. The work developed by Silva et al. (2016) brings the concept of using images to classify PQ events using the Google Image Search Engine tool. This work shows the potential of using representations of different dimensions for identification and classification. Based on the theoretic foundations of data visualization, common visualizations for the current state of power quality as well as aggregated values are reviewed and analyzed in (Kattmann and Tenbohlen, 2017). The challenges of norm visualization compliance are discussed and the work proposed a suitable plot type.

Lastly, in Alam et al. (2020) is proposed a novel algorithm employing space vector ellipse (SVE) in a complex plane to visualize PQ disturbance-events. In the proposed method, at first, the time-domain signal and a reference signal, are mapped in a complex 2D coordinates. Then, the ellipse parameters are exploited to classify and visualize nine types of disturbances. RTDS platform is used to validate the practicability of the proposed approach.

This work aims to present 2-D images from scalograms of PQ disturbance signals through the multi-resolution analysis of CWT, as a visualization tool for quality performances. To highlight the advantages of characterizing events through this method, which consists of advanced use of signal processing and image computing. In addition to these objectives, the work contributes to using signals from different sources, synthetic, from simulation or real signals, to offer a methodology that describes tools for a method of visualization. The paper shows how the characterization by this method can be useful when using various types of disturbances.

The paper is organized as follows: Section 2 goes over the principles of power quality events and the main objectives of the research proposal. Section 3 provides the the theoretical framework involving Wavelet Transform. Section 4 presents the results obtained applying Wavelet Transform to disturbances generated by functions and Section 5 presents the results obtained applying Wavelet Transform to disturbances generated from models and databases. Lastly, section VI includes the conclusion.

2. POWER QUALITY EVENTS AND RESEARCH PROPOSAL

2.1 Power Quality Disturbances

Deviations in current and voltage signals that compromise the waveform with fundamental frequency are caused by PQ issues. These problems arise when these deviations are exceeding beyond the tolerable limit, and can occur in three different ways: frequency events, voltage events, and waveform events (Jain, 2018). A variation in frequency from the nominal supply frequency above/below a predetermined level normally +-0.1% (Stones, 2003). Voltage events are variations outside its normal range. And the last one are the steady-state distortion on waveform. Fig. 1 details the types of PQ issues.

To investigate these events, it is necessary to characterize them properly. Thus, this work intends to bring some features defined by (IEEE, 2019). Table 1 describe typical values for the PQ issue approached by this paper.

Table 1. Features of investigated PQ issues (IEEE, 2019)

Categories	Spectral	Duration	Voltage Magnitude
1. Transients			
1.1. Impulsive			
1.1.1. Nanosecond	5 ns rise	< 50 ns	
1.1.2. Microsecond	1 μs rise	50 ns - 1 ms	
1.1.3. Millisecond	0.1 ms rise	> 1 ms	
1.2. Oscillatory			
1.2.1. Low Frequency	<5 kHz	0.3-50 ms	0 - 4 pu
1.2.2. Medium Frequency	5-500 kHz	20 μs	0 - 8 pu
1.2.3. High Frequency	0.5-5 MHz	5 μs	0 - 4 pu
2. Short-duration RMS variations			
2.1. Instantanous			
2.1.1. Sag		< 0.5 - 30 cycles	0.1 - 0.9 pu
2.1.2. Swell		0.5 - 30 cycles	1.1 - 1.8 pu
2.2. Momentary			
2.2.1. Interruption		0.5 cycle - 3 sec	< 0.1 pu
2.2.2. Sag		30 cycle - 3 sec	0.1 - 0.9 pu
2.2.3. Swell		30 cycle - 3 sec	1.1 - 1.4 pu
2.3. Temporary			
2.3.1. Interruption		>3 sec - 1 min	< 0.1 pu
2.3.2. Sag		>3 sec - 1 min	0.1 - 0.9 pu
2.3.3. Swell		>3 sec - 1 min	1.1 - 1.2 pu
3. Waveform distortion			
3.1 Harmonics	0 - 9 kHz	steady state	0–20%

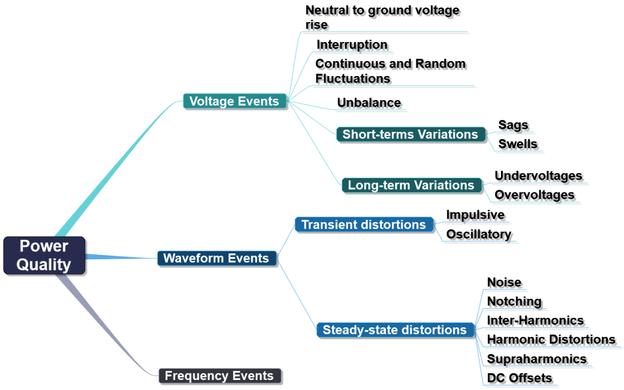

Fig. 1. Power Quality Issues

2.2 Methodology

This paper will fulfill the objective of carrying out an analysis of quality events using scalograms of the wavelet transform. For this, the signals for analysis come from three types of sources: equations, models of three-phase electrical systems in Simulink, and real signals from databases.

(1) **Equations:** The mathematical functions in the form of equations were obtained in (Igual et al., 2017), where it is possible to obtain the codes for general signs.
(2) **Power Systems Models:** The models are transmission (Salles, 2020) distribution (Almeida, 2020) systems, modeled by the authors and are available in databases with open access.
(3) **Real Signal from Databases:** For this research, two databases were chosen to provide two types of signals and real measurements, for voltage sags (de la Rosa; A. Agüera-Pérez; José Carlos Palomares-Salas; J. M. Sierra-Fernández, 2017) and impulsive transients (de-la Rosa; A. Agüera-Pérez; J. C. P. Salas; J. M. Sierra-Fernández, 2017).

In this way, after obtaining these signals, an advanced signal processing technique is applied, multi-resolution analysis of the wavelet transform. As a result, the scalograms will allow an alternative visualization of quality problems. Each signal with its respective scalogram is analyzed and discussed. The results of this work will be these representation with descriptions and discussions about the images. Fig. 2 resumes the methodology.

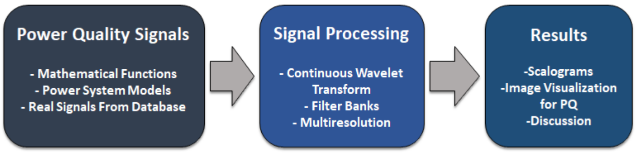

Fig. 2. Methodology Scheme

3. WAVELET TRANSFORM

With the advances in the complexities of current and future grid, an evolution in the signal processing that identify certain parameters and patterns of behaviour of the system will be necessary so that these events can be classified correctly (Ribeiro et al., 2013). In this way, the Wavelet Transform is one of those advanced tools that performs a significant role in feature extraction for the pattern recognition of PQ disturbances (Ibrahim and Morcos, 2002).

The Wavelet Transform performs the signal mapping in time and frequency, separating the input signal into different frequency bands in which the transients caused by the system's transitions are more evident (Sena et al., 2018). This process is named multi-resolution analysis (MRA).

The signal to be analyzed is decomposed into various scales of a short term waveform called the ”mother wavelet”. According to Xu et al. (2006), this typical wavelet is a fast decaying oscillating waveform with zero mean value.

The Continuous Wavelet Transform (CWT) is one of the derivations of Wavelet Transform and allows the analysis of non stationary signals at multiple scales and uses a window to extract signal segments. According to Santoso et al. (1996), the CWT is defined in (1):

$$C(a,\tau) = \int \frac{1}{\sqrt{a}} \Psi(\frac{t-\tau}{a}) x(t) dt, \qquad (1)$$

where C is the transformation, a is the scale factor,τ is the translation time, Ψ is the mother wavelet function and $x(t)$ is the input signal in function of time.

When the wavelet is contracted ($a < 1$) the wavelet offers high temporal resolution and when the wavelet is dilated ($a > 1$) the wavelet offers high spectral resolution. The first case is ideal for transient events while the second case is best fitting for determining frequencies in phenomena in steady-state.

The main properties that the wavelet function must obey are that of finite energy and the admissibility condition (zero frequency component), described in (2) and (3) respectively (Addison, 2017), where E is the energy of the wavelet:

$$E = \int_{-\infty}^{\infty} |\Psi(t)|^2 dt \ < \infty, \qquad (2)$$

$$\int_{-\infty}^{\infty} \Psi(t) dt \ = 0 \qquad (3)$$

The MRA allows for both good time resolution at high frequencies and good frequency resolution at low frequencies (Silveira et al., 2007). This analysis can be computed through filter banks, which are set of filters that compose the signal in specific frequency ranges. Usually these filter banks are composed of several low-pass and high-pass filtering branches. Each high-pass filter produces a detailed version of the original signal and the low-pass a smoothed version (de Souza et al., 2018).

In the literature there are several wavelet functions, such as Morlet, Shannon, Mexican Hat, Meyer, Gabor, and Gaussian, which can be selected according to the nature of the signal to be analyzed (Bronzini et al., 2007). The wavelets are generated from the mother wavelet by dilations and translations of these parameters, resulting in several wavelet basis functions. Fig. 3 shows some examples of mother wavelets.

The choice of each mother wavelet must be consistent with the desired application, making it model the acquired signal accurately. Thus, an appropriate choice of a mother wavelet is not only elegant and useful, but it is also efficient Galli et al. (1996). For this work, the mother wavelet chosen was Morlet.

In order to visualize the entire process, representing both time and frequency localization of wavelet transform, the scalogram is used. This is is a graphical representation tool that maps the signal into a 2-D domain of time and frequency. The correlation can be represented using RGB palettes such as the Jet Colormap, where blue and red colors represent the minimum and maximum intensities of energy respectively. The wavelet scalogram is defined in (4).

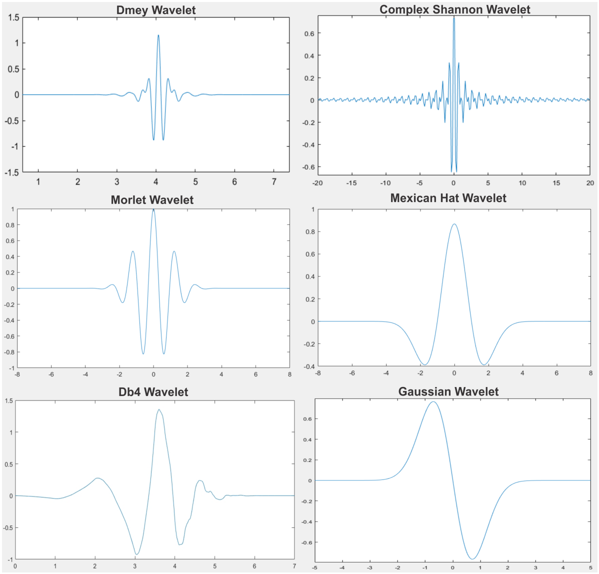

Fig. 3. Examples of different types of mother wavelets

$$WS(a,\tau;\Psi) = |CWT(a,\tau;\Psi)|^{\,2}, \qquad (4)$$

In this work, the CWT method with MRA is performed to extract, through time-frequency analysis, a 2-D scalogram representation of the voltage signals, allowing the PQ disturbances differentiation and characterization.

4. DISTURBANCES GENERATED BY FUNCTIONS

In this section were used functions to generate the disturbances, according to Igual et al. (2018). The chosen sampling frequency was 30kHz, the nominal electrical frequency was set at 60Hz and all disturbances have 20 cycles.

The Equation 5 represents a Voltage Sag disturbance, where α value is between 0.1 and 0.9. Fig. 4 shows the scalogram of this event, with the start time equal to 0.025s and final time equal to 0.200s.

$$v(t) = A(1 - \alpha(u(t-t_1) - u(t-t_2)))sin(\omega t - \phi) \qquad (5)$$

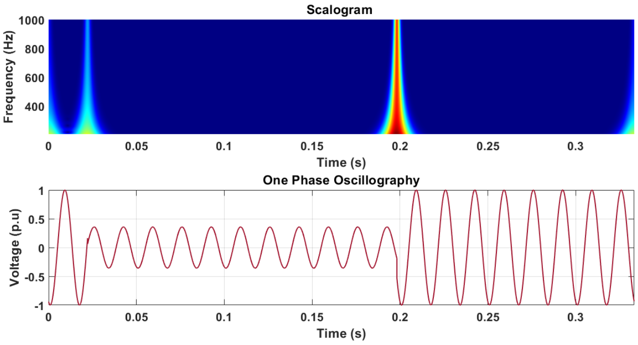

Fig. 4. Voltage Sag Generated by Equation

Equation 6 describes a Voltage Swell disturbance, where $0.1 \leq \beta \leq 0.8$. In Fig. 5 is possible to visualize the scalogram of this event, with the start time equal to 0.066s and final time equal to 0.233s.

$$v(t) = A(1 + \beta(u(t - t_1) - u(t - t_2)))sin(\omega t - \phi) \quad (6)$$

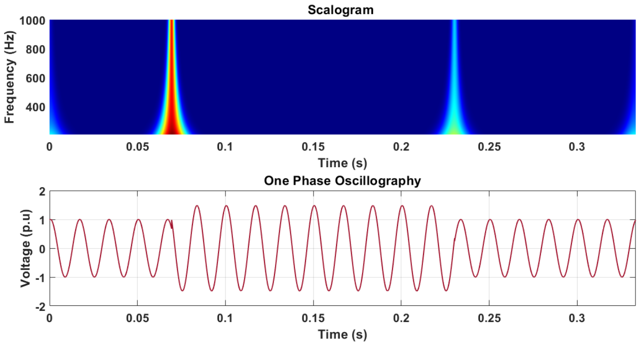

Fig. 5. Voltage Swell generated by Equation

A Interruption Disturbance is represent in Equation 7, where ρ value is between 0.9 and 1.0. The scalogram of this event can be visualized in Fig. 6 with the start and final time equal to 0.046s and 0.325s respectively.

$$v(t) = A(1 - \rho(u(t - t_1) - u(t - t_2)))sin(\omega t - \phi) \quad (7)$$

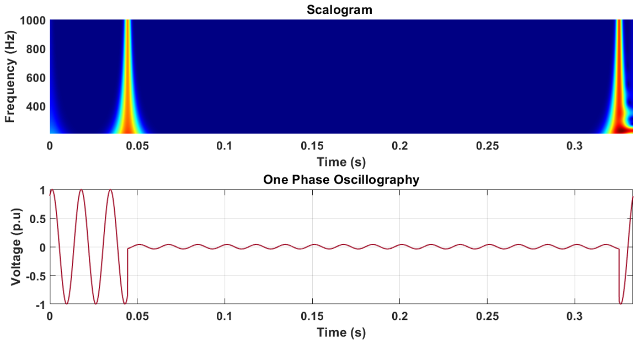

Fig. 6. Interruption generated by Equation

In these first three scalograms it is possible to see the characteristic curves that represent both initial and final time of the events. The three situations differ only in the colors within those curves. When a Voltage Sag occurs, the second curve is filled with red color. When a Voltage Swell occurs, the first curve is now which presents the red color inside. In case a interruption occur, both curves are filled with this coloring.

The Equation 8 represents a Impulsive Transient, where ψ value is between 0.222 and 1.11. Fig. 7 shows the scalogram of this event, with the start time equal to 0.066s.

$$v(t)=A[sin(\omega t-\phi)-\psi(e^{-750(t-t_a)}-e^{-344(t-t_a)})((u(t-t_a)-u(t-t_b)))] \quad (8)$$

Equation 9 describes a Oscillatory Transient, where $-\pi \leq \upsilon \leq \pi$. In Fig. 8 is possible to visualize the scalogram of this event, with the start time equal to 0.241s.

$$v(t)=A[sin(\omega t-\phi)+\beta e^{-(t-{}_1)/\tau}sin(w_n(t-t_I)-\upsilon)((u(t-t_{II})-u(t-t_I)))] \quad (9)$$

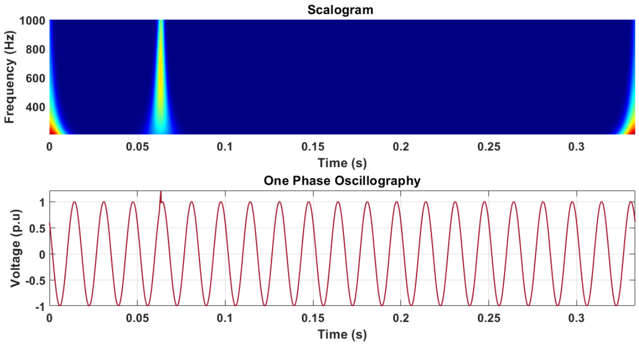

Fig. 7. Transient Impulsive generated by Equation

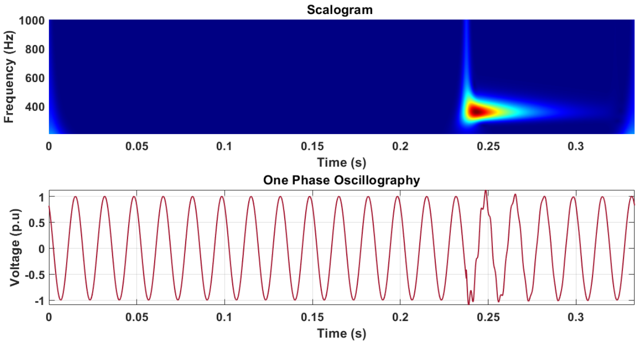

Fig. 8. Transient Oscillatory generated by Equation

These last two scalograms are very characteristic for each event. In the case of Transient Impulsive, a long shape curve is perceived. In the case of Transient Oscillatory, the shape of the curve in the scalogram is more compressed, highlighting the individuality of the two events and enabling their identification.

The results shown so far prove that it is possible to visualize disturbances by means of scalograms even when they are generated through functions. It is important to highlight that when simulating real and more complex events, other disturbances can appear at the same time, as is the case with harmonics. The next section will cover this more specifically.

5. DISTURBANCES GENERATED FROM MODELS AND DATABASES

These results use signals generated from models of a distribution system and a transmission system. The disturbances were applied to them and the signals were saved for analysis. The first system is a 240V distribution grid. The second model is a 750 kV transmission system modeled in Simulink. Both models are available in the associated references in the methodology section. These are simplified models, which use values typical of power systems. The nominal electrical frequencies of the systems are 60Hz. Finally, real signals (50Hz fundamental) are also used to compare and analyze quality performance. The list below details the investigated events.

- **Oscillatory Transient:** In this event, only model signals are used. They were generated by switching heavy capacitive loads to cause the oscillatory transient.

- **Impulsive Transient:** For this event, signals from the first models that correspond to the distribution system and a real signal are used. In the case of the model, the electrical discharge of a lightning bolt is simulated to generate the event.
- **Voltage Sag:** These results uses the three signal sources, both the models and the actual signal. In the models, this voltage sag is caused by three-phase faults.

Fig. 9 shows the scalogram of an oscillatory transient from distribution system model. Fig. 10 shows the scalogram of an oscillatory transient from transmisson system model.

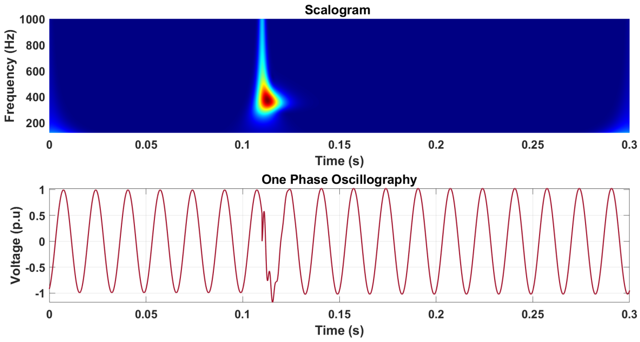

Fig. 9. Oscillatory Transient from Distribution System Model (Capacitor Bank Switching)

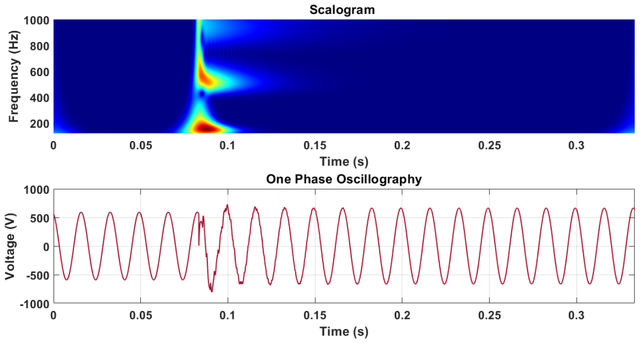

Fig. 10. Oscillatory Transient from Transmission System Model (Capacitor Bank Switching)

In these scalograms, it is possible to perceive a similarity in the frequency range that presents concentration as a function of time. The shapes formed by the images are well distributed given the proportions of the systems, thus characterizing a visualization of the oscillatory transient, with similarity for different cases.

Fig. 11 and Fig. 12 show the scalograms of impulsive signals from the distribution system model and real database, respectively.

In these two scalograms, coming from the signals with impulsive transient, the image generated apart from that signal is well characterized. The frequency concentrated at the time of the event is very similar and very short in duration. However, it is possible to perceive in the real signal that other frequencies are present varying in time. It highlights that the real signal presents other issues, but the model only proposes to apply what is programmed, while in the real it may contain other types of frequency such as noise or even harmonics from the grid.

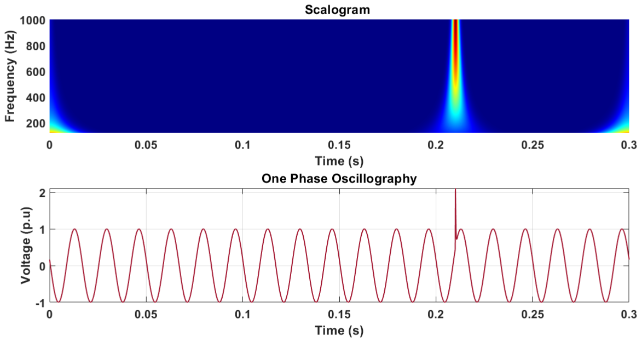

Fig. 11. Impulsive Transient from Distribution System Model

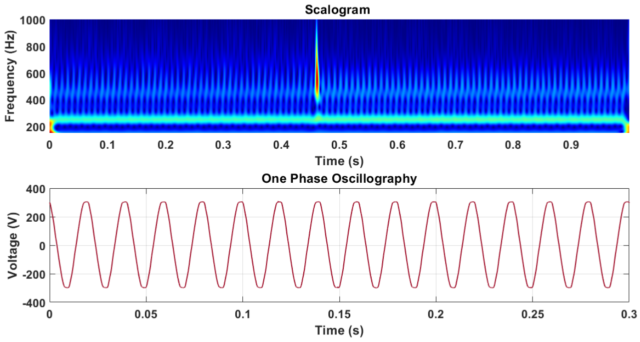

Fig. 12. Impulsive Transient from Real Signal Database

Finally, the results shown in Fig. 13 and Fig. 14 show the voltage sag from the Distribution and Transmission systems model, respectively. Fig. 15 and 16 show two real voltage sag signals, 10 % and 71% respectively.

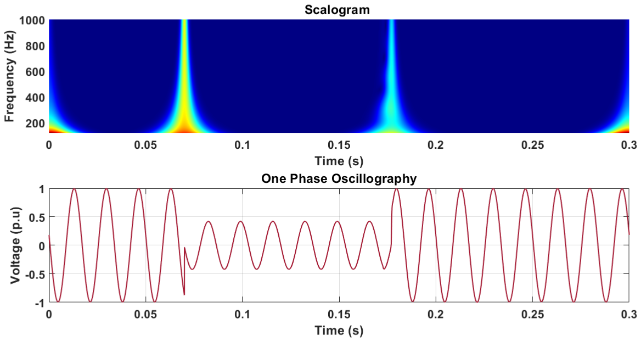

Fig. 13. Voltag Sag from Distribution System Model

As in previous events, the scales can also characterize the issues in a similar way for each case. However, for real events, the presence of the 5th harmonic of this real signal is evident.

The results highlight the alternative of visualizing power quality problems. The scalograms characterized the signals well for different cases, making it possible to generate a correlation of similarity between the event and the image generated.

Another important point was the possibility of visualizing more than one quality problem present in the real signals. In the voltage sag scalograms, this became more evident,

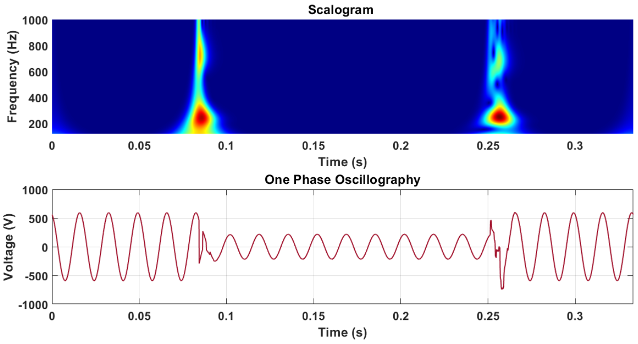

Fig. 14. Voltag Sag from Transmission System Model

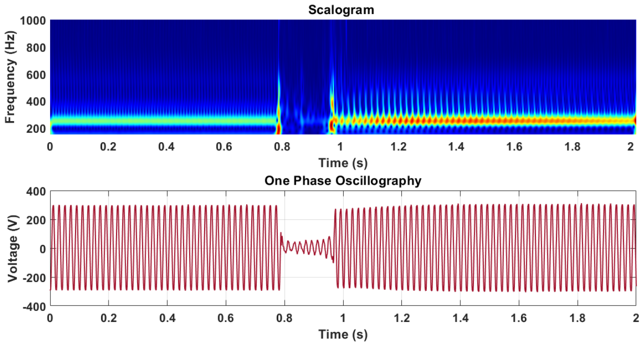

Fig. 15. Voltag Sag from Real Signal Database (10%)

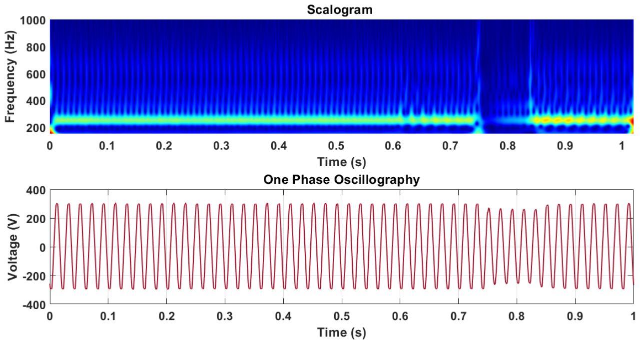

Fig. 16. Voltag Sag from Real Signal Database (71%)

they are called enkaptic events. In addition to being intertwined, one can influence the other, as highlighted in Fig. 15, which after the voltage disturbance, the 5th harmonic became stronger.

6. CONCLUSION

This work managed to dismantle an alternative way of visualizing power quality performances. Through signal processing, using CWT, it was possible to obtain 2-D scalograms of the 1-D signals. It allowed the use of a color map to detect the frequencies that characterized the event in this time-frequency analysis.

In addition to bringing a way of visualizing these quality issues, it also made it possible to feed applications that are favored with this type of representation. These applications become increasingly present in the context of Smart Grids, which is also marked by the use of artificial intelligence.

Through this method, the enkaptic phenomena of energy quality are also highlighted, showing that in the real application these events are not dissociated. Thus, visualizing and representing this influence and iteration becomes essential. Finally, the databases and the program for extracting the scales are available in the references indicated in the text. Thus, the method is available to the scientific and professional community.

Future works should use sets of real measurements to compile and generate reference material regarding scalograms to visualize quality performance. A power quality characterization **vade mecum** could allow researchers and professionals to consult the document in their projects. The use of methods for image classification should explore these contributions and develop works aimed at the pattern recognition of PQ disturbances.

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