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Harmonic and Interharmonic Detection in Power Quality Applying the Wavelet Synchrosqueezing Transform

Detección de Armónicos e Interarmónicos en la Calidad de Energía Aplicando la Transformada Wavelet Synchrosqueezing

Alberto Gudiño-Ochoa[*1], **Jaime Jalomo-Cuevas**[1], **Daniel Sánchez-Jiménez**[1], and **Raquel Ochoa-Ornelas**[2]

[1] *National Technological Institute of Mexico/Ciudad Guzman Institute of Technological,Department of Electricity and Electronics,*
Av. Tecnológico 100, Carretera al Fresnito, Ciudad Guzmán, Jal., México, 49100.
albertogudo@hotmail.com, jaime.jc@cdguzman.tecnm.mx, danieldsh8@hotmail.com

[2] *National Technological Institute of Mexico/Ciudad Guzman Institute of Technological, Systems and Computing Department,*
Av. Tecnológico 100, Carretera al Fresnito, Ciudad Guzmán, Jal., México, 49100.
raquel.oo@cdguzman.tecnm.mx

Abstract

Power quality has become an increasing problem as harmonic frequencies begin to appear in renewable energy sources and non-linear systems connected to the electrical grid. Interharmonics are frequencies that are not multiples of the fundamental frequency and make harmonic analysis more complicated. This is a challenge for companies and users to improve power quality, so this article proposes the use of the Wavelet Syncrosqueezing Transform (SSWT) method in time-frequency analysis. SSWT proves to have better anti-noise properties and high resolution compared to other methods, such as Continuous Wavelet Transform (CWT) and Short Time Fourier Transform (STFT). The method is validated on simulations and data collected from renewable energy sources, as well as real-time measurements caused by the flicker effect. The results demonstrate the effectiveness of the method in the analysis of signals that present variations in time and frequency.

Keywords— Harmonics, Renewables Sources, Power Quality

Resumen

La calidad de la energía se ha convertido en un problema cada vez mayor a medida que comienzan a aparecer frecuencias armónicas en fuentes de energías renovables y sistemas no lineales conectados a la red eléctrica. Los interarmónicos son frecuencias que no son múltiplos de la frecuencia fundamental y hacen que el análisis armónico sea más complicado. Este es un desafío para las empresas y los usuarios para mejorar la calidad de la energía, por lo que este artículo propone el uso del método Wavelet Syncrosqueezing Transform (SSWT) en el análisis de tiempo-frecuencia. La SSWT demuestra tener mejores propiedades antirruido y alta resolución en comparación con otros métodos, como la Transformada Wavelet Continua (CWT) y la Transformada de Fourier de Tiempo Corto (STFT). El método es validado en simulaciones y datos recopilados de fuentes de energías renovables, como así también en mediciones en tiempo real causado por el efecto flicker. Los resultados demuestran la efectividad del método en el análisis de señales que presentan variaciones en tiempo y frecuencia.

Palabras clave— Armónicos, Fuentes Renovables, Calidad de la Energía

[*]Autor de correspondencia

I. Introduction

Power quality refers to the suitability of the electrical power supplied to the equipment for its correct operation without affecting its performance [1, 2]. The current context of the increase in non-linear loads in modern power systems, electrical machines, electric arc furnaces, frequency inverters and integrations of renewable energy sources have repercussions on the generation of harmonic and interharmonic content for the analysis of power quality [3, 4, 5].

This influences the operation of the equipment connected to the network, causing overheating in the equipment, the flicker effect, vibrations and malfunctions [6, 7]. For this reason, it is necessary to carry out an early detection of harmonics and interharmonics to avoid damage and guarantee quality in power generation.

The use of traditional methods in signal analysis, such as the Fast Fourier Transform (FFT), is not ideal since they present imprecision [8, 9] and are not useful for the analysis of non-stationary signals, which is one of the main problems facing power quality [10, 11]. This case is like the Discrete Fourier Transform (DFT) for the detection of harmonic content due to the lack of time information [12].

In other investigations, it has been shown that methods such as the Wavelet Transform (WT) by decomposing the signal into frequency bands cause inaccurate estimates of harmonics [13]. The S-transform has been useful for the classification of power quality disturbances [14]; however, the window width is inversely proportional to the frequency, causing an imprecise estimation of interharmonics [15].

Some techniques for time-frequency analysis for non-stationary signals with variations, such as the Short-Time Fourier Transform (STFT) and the Continuous Wavelet Transform (CWT), have been useful. However, they are not precise enough when the signals tend to be almost stationary [16, 17]. The STFT presents defects in frequency leakage due to asynchronous transformations, unless the type of window is correctly selected, this decreases the frequency resolution [18].

The Wavelet Synchrosqueezing Transform (SSWT) is a nonlinear time-frequency analysis method based on CWT [19, 20], which has been useful in multicomponent signals that present oscillating modes in signal reconstruction [21, 22], thanks to the assignment of the CWT coefficient value to a different location in the frequency-time plane.

One of the main advantages in addition to anti-noise is the resolution of time-frequency curves, including signals that are weakly variable with respect to time. This algorithm has been applied to signal analysis, mechanical fault diagnosis, noise removal, showing good results [23, 24, 25, 26, 27, 28, 29].

This paper proposes the use of SSWT for the analysis of harmonics and interharmonics generated by synthetic signals and renewable energy sources in comparison to other techniques used in non-stationary signals.

The theory of the algorithm is presented in Section II. Section III provides the results of the method against simulations, first with a synthetic signal, then with a voltage signal from a three-phase induction motor being fed with harmonic and interharmonic content, which was simulated with Matlab and Simulink software. For renewable energy sources, a photovoltaic system is implemented with the same software, current signals are processed, and the SSWT is verified with measurements from a real-time dataset of solar panels for one day; additionally, it is tested on generated current signals from a detailed model of a wind turbine-driven doubly fed induction generator (DFIG) in Simulink. The study concludes in Section IV with the validation of the method with signals acquired from a motor-generator system varying the frequency resulting in the flicker effect. The best resolution is verified at frequencies that are not a multiple of the fundamental supply frequency.

II. Wavelet Synchrosqueezing

II.1. Theory

The applications of the SSWT include the analysis of signals in power systems [30] and mechanical vibrations [31], its main characteristic is the oscillating mode, in other words, being the set of components modeled in frequency and amplitude how it is expressed by (1).

$$s(t) = \sum_{k=1}^{K} A_k(t)\cos(2\pi\phi_k(t)) \tag{1}$$

where $A_k(t)$ is the amplitude, ϕ_k is considered as the phase, in both the frequency and amplitude do not vary, reallocating the energy in a single-frequency direction, therefore, the time resolution of the signal.

The signal can be accurately reconstructed to the original by applying the synchrosqueezing algorithm. The SSWT is based on the continuous wavelet transform W_s of the signal $s(t)$ defined by (2).

$$W_s(a,b) = \int s(t)a^{-\frac{1}{2}} \cdot \psi\left(\frac{t-b}{a}\right)dt \tag{2}$$

where s and b are parameters of the mother wavelet, ψ is the appropriately chosen wavelet. Applying Plancherel's theorem, we rewrite $W_s(a,b)$, the Continuous Wavelet Transform of s with respect to ψ, is (3).

$$\begin{aligned} W_s(a,b) &= \frac{1}{2\pi}\int \hat{s}(\xi)a^{\frac{1}{2}}\hat{\psi}(a\xi)e^{ib\xi}d\xi \\ &= \frac{A}{4\pi}\int [\delta(\varsigma-\omega)+\delta(\varsigma+\omega)]\sqrt{a}\hat{\psi}\cdot e^{ib\varsigma}d\varsigma \\ &= \frac{A}{4\pi}\sqrt{a}\hat{\psi}(a\omega)e^{ib\omega} \end{aligned} \quad (3)$$

if $W_a(a,b) \neq 0$ or any (a,b), the instantaneous frequency $\omega(a,b)$ is obtained as (4).

$$\omega_s(a,b) = -i(2\pi W_s(a,b))^{-1}\frac{\partial}{\partial b}W_s(a,b) \quad (4)$$

The time scale plane transfers its information to the time-frequency plane by relocating points in (b,a) to $(b,\omega_s(a,b))$ in an operation called synchrosqueezing. This expression is given by equation (5).

$$T_s(\omega_1,b) = (\Delta\omega)^{-1}\sum_{a_k:|\omega(a,b)-\omega_1|\leq\Delta\omega/2} W_s(a_k,b)a_k^{-\frac{3}{2}}\Delta a_k \quad (5)$$

$W_s(a,b)$ was calculated only in discrete values a_k, with $a_k - a_{k-1} = (\Delta a)_k$, for Equation (5) the frequency is determined in the intervals $\left[\left(\omega_1 - \frac{\Delta\omega}{2}\right), \left(\omega_1 + \frac{\Delta\omega}{2}\right)\right]$ the complete calculation is proved [32]. The signal after synchrosqueezing can be reconstructed in such a way as to obtain (6).

$$\int_0^\infty W_s(a,b)a^{-\frac{3}{2}}da = \int_0^\infty \overline{\hat{\psi}(\xi)}\frac{d\xi}{\xi}\cdot\frac{1}{2\pi}\int_0^\infty \hat{s}(\zeta)e^{ib\zeta}d\zeta \quad (6)$$

Setting $C_\psi = \frac{1}{2}\int_0^\infty \overline{\hat{\psi}(\xi)}\frac{d\xi}{\xi}$, we obtain (under the assumption that s is real, so that $\hat{s}(\xi) = \overline{\hat{s}(-\xi)}$, therefore $s(b) = \pi^{-1}\Re\left[\int_0^\infty \hat{s}(\xi)e^{ib\xi}d\xi\right]$. Applying a piecewise constant approximation corresponding to the binning at a, this becomes in (7).

$$\begin{aligned} s(b) &= \Re\left[C_\psi^{-1}\sum_k W_s(a_k,b)a_k^{-\frac{3}{2}}(\Delta a)_k\right] \\ &= \Re\left[C_\psi^{-1}\sum_l T_s(\omega_l,b)(\Delta\omega)\right] \end{aligned} \quad (7)$$

II.2. Synchrosqueezing algorithm

The SSWT uses the CWT and its first derivative, the algorithm consists of three steps:

Step 1) Obtain the CWT of the input signal, in the instantaneous frequency capture an analytical wavelet is used.

Step 2) The instantaneous frequencies are extracted from the CWT output; this phase transformation is proportional to the first derivative with respect to the translation. The partial derivative is divided by the wavelet transform and $i2\pi$ to obtain the instantaneous frequency.

Step 3) The "squeeze" is applied in regions of the CWT where the phase transformation is constant. Reallocation produces a cleaner output of the SSWT compared to the CWT.

III. Study and performance analysis

The use of renewable energies, such as wind and solar energy, has increased the penetration of harmonic and interharmonic content [33, 34, 35]; likewise, new energies in the industry, such as the use of induction motors, have impacted in the power quality [36]. Therefore, the detection of these disturbances is essential for their mitigation and control.

The performance of the SSWT method is compared with other traditional methods in different cases, a non-stationary signal with harmonic and interharmonic content, a noisy signal generated by an induction motor, renewable energies connected to the grid such as a photovoltaic and wind system. Finally, the application and effectiveness of the SSWT in experimental measurements associated with the flicker effect are demonstrated.

III.1. Harmonics and interharmonics in non-stationary signal

A non-stationary signal is one that changes its properties with respect to time, that is, it presents variations in its frequency in different periods of time. The synthetic signal $x(t)$ is generated in such a way that:

$$x(t) = \begin{cases} \sin(2\pi 60t) & 0 < t < 1\text{s} \\ 0.2\sin(2\pi 78t) + 0.3\sin(2\pi 105t) & 0.1 < t < 0.35\text{s} \\ 0.8\sin(2\pi 137t) & 0.35 < t < 0.45\text{s} \\ 0.9\sin(2\pi 178t) & 0.45 < t < 0.6\text{s} \\ 0.6\sin(2\pi 217t) + 0.2\sin(2\pi 348t) & 0.6 < t < 0.89\text{s} \end{cases} \quad (8)$$

The signal contains interharmonic frequencies at 78 Hz, 105 Hz, 137 Hz, 178 Hz, 217 Hz and 348 Hz, their amplitudes correspond to 0.2, 0.3, 0.8, 0.9, 0.6 and 0.2, the sampling frequency is 1200 Hz.

The generated signal is observed in Figure 1a; likewise, the SSWT compared to other methods, such as CWT and STFT, demonstrate a more accurate estimate of the harmonic content generated in figures 1b-1d, this occurs due to the inherent logarithmic nature of the function extractor, using an adaptive window. Wavelets enjoy superior instantaneous amplitude and frequency rapping, making them ideal for evolution processes.

Table 1 shows the deficiency of CWT for the actual values of the non-stationary signal, while SSWT has a smaller relative error at most values of the identified interharmonic frequencies.

Table 1: *Accuracy and relative error for the detection of harmonics and interharmonics in a non-stationary signal*

Value (Hz)	Detection Value (Hz) CWT	Detection Value (Hz) SSWT	Relative Error (%) CWT	Relative Error (%) SSWT
60	59.35	60.41	1.08	0.68
78	78.43	78.94	0.55	0.55
105	102.7	105.5	2.15	0.47
137	134.5	137.8	1.78	0.58
178	176.2	180.1	0.98	1.17
217	216.7	220	0.11	1.38
348	339.8	349	2.35	0.28

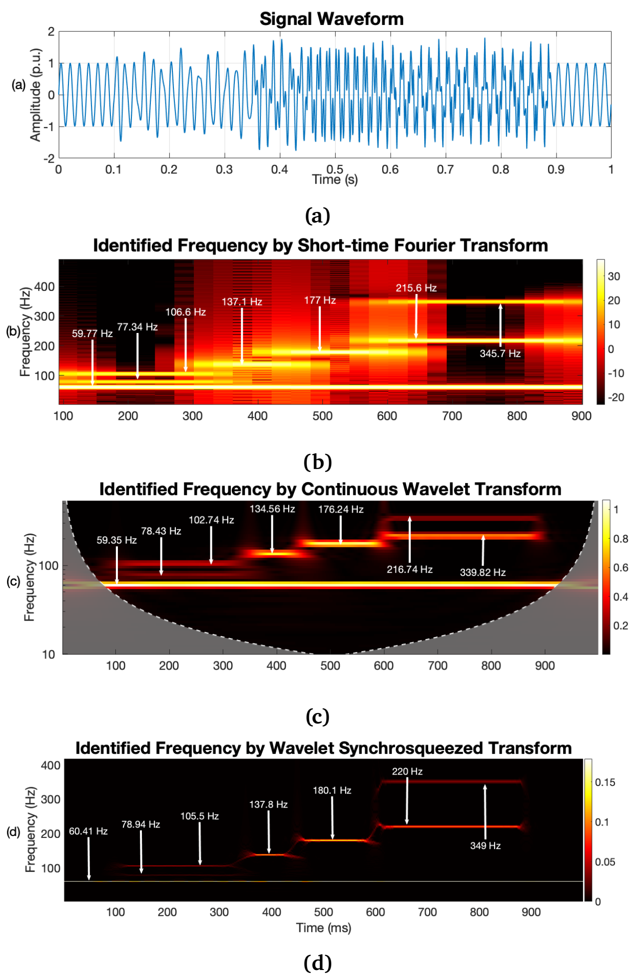


Figure 1: *Detection of harmonics and interharmonics*

III.2. Frequency variations on induction motor

Induction motors are a source of generation of harmonic content, either due to their construction of the magnetic circuit or the asymmetries they present. Adjustable speed drives are a main source of motor harmonic and interharmonic generation [37]. In Simulink, an induction motor at 100 HP, 460 V, 60 Hz at 1780 RPM was used. This model is shown in Figure 2. It was fed with two programmable AC power sources at 120 Vrms at 60 Hz and a harmonic generation of amplitude 5 and 2 (p.u.), with a phase 25 and 0. The second programmable source was configured at 220 Vrms at 50 Hz, with variations in frequency of 10 Hz and harmonic generation of amplitude of 3 and 2 (p.u.), with phases of -15 and 35, the sampling frequency was 10 kHz.

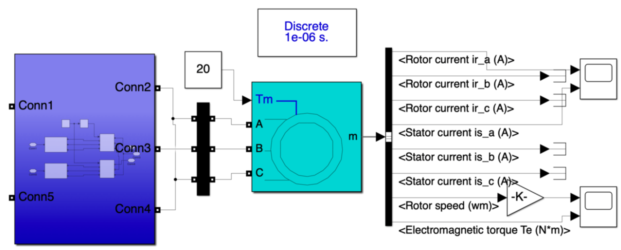


Figure 2: *Induction Motor Model*

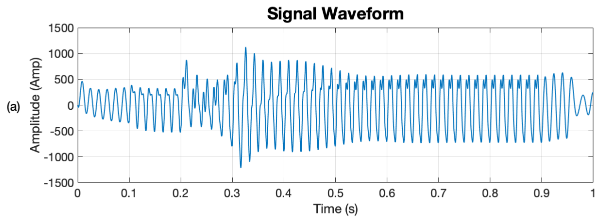
For this case, the harmonics and interharmonics of the voltages are directly associated with the frequency variators, which control the speed of the motor, so the harmonic and interharmonic currents that appear are considered, the values of one phase of the motor are taken. In the harmonic analysis with the FFT, interharmonic components were found at 52 Hz, 53 Hz, 59 Hz, 63 Hz, 100 Hz, the other frequencies being integer multiples of the fundamental frequency at 60 Hz, 120 Hz, 150 Hz and 180 Hz.

The application of the STFT shows spectral leaks in Figure 3b, while the CWT and SSWT show to be suitable methods for the analysis of non-stationary signals in electrical machines, however, the SSWT shows a smaller relative error in the estimates of the harmonic and interharmonic content, in addition it does not present any type of spectral leak having a better resolution, the comparison of these values is presented in Table 2.

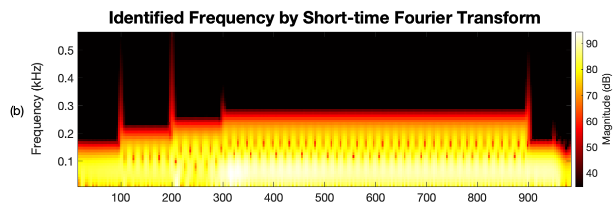
Table 2: *Detection of harmonics and interharmonics and relative error on induction motor*

Value (Hz)	Detection Value (Hz) CWT	Detection Value (Hz) SSWT	Relative Error (%) CWT	Relative Error (%) SSWT
52	52.17	52.37	0.32	0.71
53	53.62	53.53	1.16	1
59	59.37	59.85	0.62	1.44
60	60.67	60	1.11	0
63	62	63	1.58	0
100	102.2	99.86	2.2	0.14
120	121.59	119.3	1.32	0.58
150	151.09	150	0.72	0
180	179.37	180	0.35	0

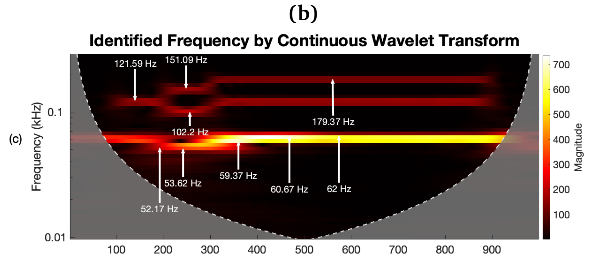
In Figure 3d the magnitude in each harmonic and interharmonic shows a better precision than the other frequencies identified by the CWT.



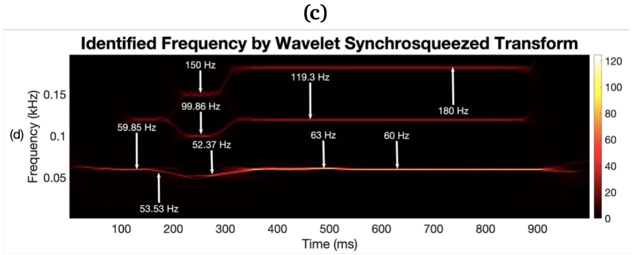
(a)



(b)



(c)



(d)

Figure 3: *Detection of harmonics and interharmonics in induction motor*

IV. Analysis of interharmonics in renewable energies

IV.1. Photovoltaic system

Inverters in photovoltaic systems (PV) are one of the main generators of harmonic and interharmonic content, harmonic analysis is essential, various studies have shown that MPPT inverters and controllers in AC/DC and DC/DC links are the main source of harmonic disturbances in the grid [33, 34].

A case of inverters in photovoltaic systems is analyzed, the system is three-phase and consists of two stages. The first stage is made up of a DC voltage boost converter, the second stage considers an inverter connected to a domestic network at 400 Vrms and 50 Hz, with a sampling frequency of 10 KHz, the model was developed in Matlab Simulink, which is shown in Figure 4.

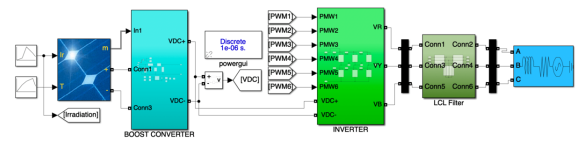


Figure 4: *Three-phase photovoltaic system model*

The most relevant parameters of the system are presented in Table 3.

Table 3: *Parameters of PV System*

Parameter	Value
Three-phase inverter circuit switching Frequency	5 KHz
Rated Power	100 KW
Filter LCL	500 μH, 100 μF
Duty Cycle	0.2
Energy Storage Inductor	3 mH
DC Side Capacitance	3227 μF
V_{MPPT}	270-300 V

Figure 5d shows the resolution of the SSWT compared to the low performance of the STFT, the CWT manages to have a resolution with the variation of time-frequency, however, it presents spectral leaks at frequencies close to the fundamental one, wich is observed in Figure 5c, on other words, the SSWT manages to perceive the interharmonics present in magnitudes that allow their visualization above 200 Hz.

To verify the usefulness and resolution of this method, the solar current signal of a panel system was analyzed in winter, the data set was provided at the Clemson University Power Systems Conference (PSC) 2016 for "Dynamic loads and load method microgeneration for a Housing Management System" in the Southeast of Brazil [38].

Results on Figure 6 analyze harmonics current from a daily output power generation sampled each 5 minutes. These values of current represent an average steady-state at fundamental frequency.

It this case, it is recommended to use alternating current signal output from the inverter at maximum power output generation of PV-System, wich according with Standar IEEE-519, must be less 5% THD (total harmonic distortion) [39]. The SSWT in Figure 6d demonstrates the presence of interharmonics, it is possible to know what frequency occurs in certain time intervals.

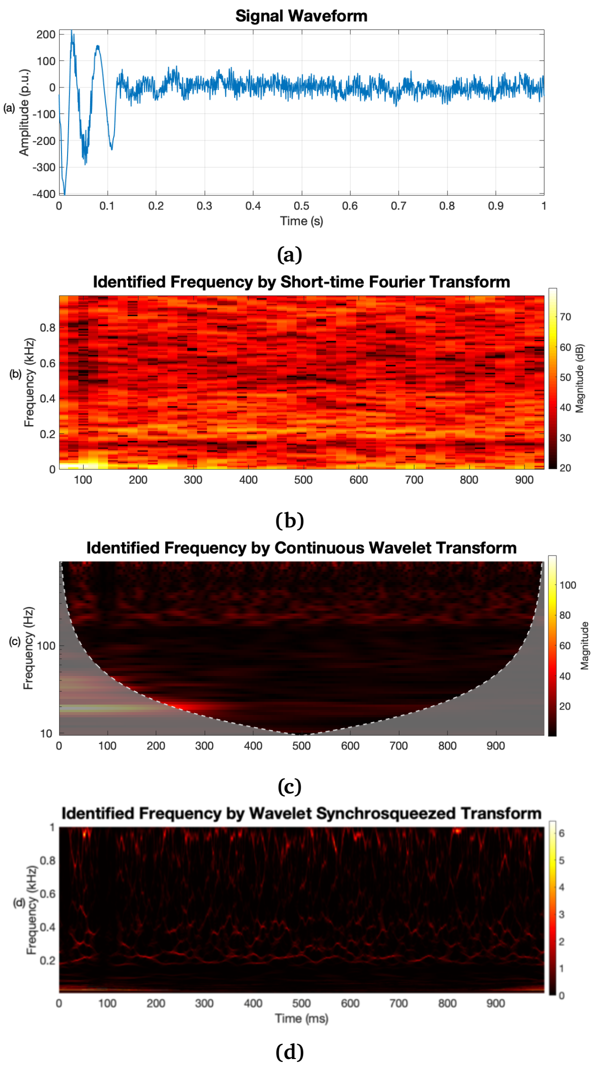


Figure 5: *Detection of harmonics and interharmonics in PV System*

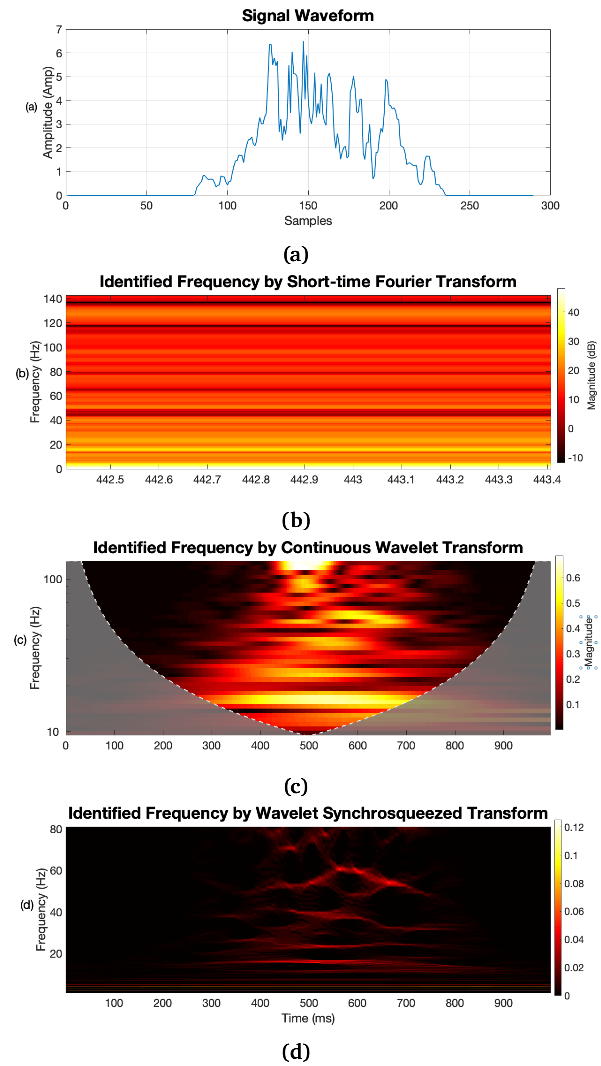


Figure 6: *Detection of harmonics current and interharmonics in PV System*

IV.2. Wind farm

The method was verified in a model of a system connected to the electricity grid generated from wind energy in Simulink, the sampling frequency is around 748 Hz and a total energy of 9 MW, the system is visualized in Figure 7. This model was suitable for analyzing harmonic content over short periods of time. It is made up of six 1.5 MW wind turbines connected to a 25 kV distribution system, the energy exported is 120 kV.

The turbines use a doubly fed induction generator (DFIG), the motor stator is connected directly to the 60 Hz grid and the wind speed is maintained at 15 m/s. The signal corresponds to the triphasic current, again in Figure 8d the precision in resolution of the SSWT is shown, the other two methods present a poor resolution.

Considering the inclusion of renewable energy sources in solar panels and wind generators, the use of SSWT is feasible, because it demonstrates a high resolution compared to other traditional methods against harmonic analysis, additionally, it should be noted that the combination of this technique in signal analysis with machine learning and deep learning [40, 41], offer reliable results, as well as precise estimates in the regulation and control of harmonics.

V. Results and measurement experiments

One of the main effects of the high generation and disturbances of interharmonic content is the flicker effect [42], this effect is visible as a flicker in intensity in illuminations [43] and is mainly reflected in voltage fluctuations in the electrical network. Being the interharmonics the main cause of the flicker effect and low

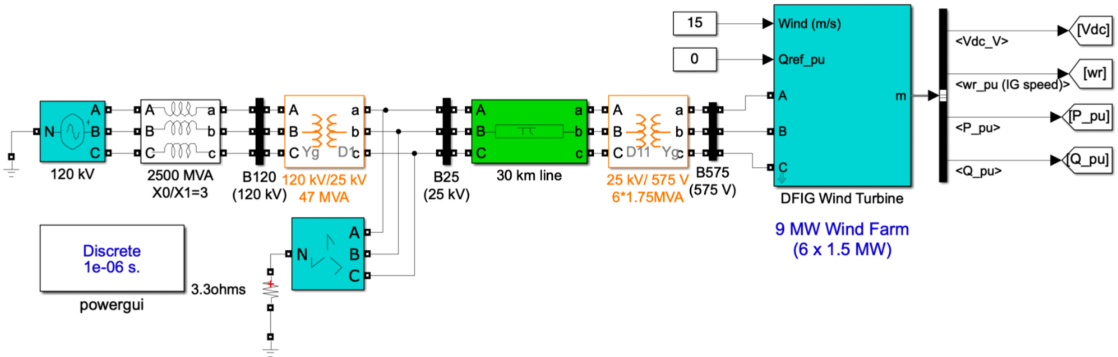


Figure 7: *Wind Farm – DFIG Model*

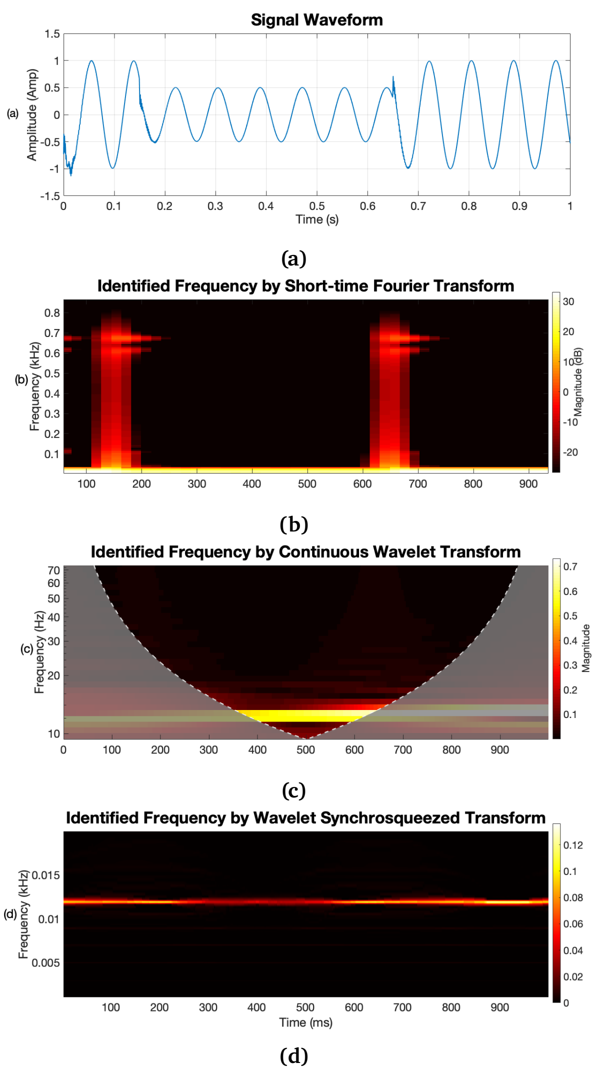


Figure 8: *Detection of harmonics current and interharmonics in Wind Farm*

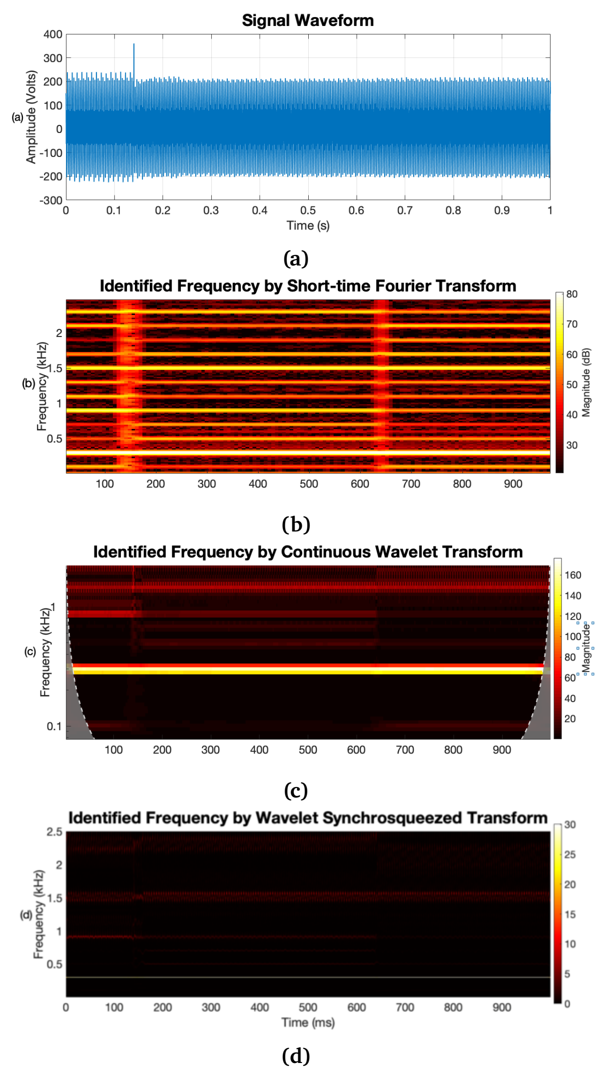


Figure 9: *Detection of harmonics current and interharmonics in flicker Signal*

performance of equipment connected to the network, it is considered as an important affectation in the power quality.

For this reason, a flicker signal produced from the variation of the frequency [37] was acquired, with a Danfoss VLT Micro speed variator for a module made up of an ABB three-phase induction motor at 1610 RPM and 220 RPM/400 Volts, in conjunction with a synchronous motor with resistive load, to visualize this effect a 100 W incandescent bulb was added.

The voltage signal was acquired with a National Instruments USB-6009 DAQ and a ZMPT101B AC voltage sensor, thus measuring one of the phases of the motor with a DC load. Figure 9a shows the generated signal, with a sampling frequency of 5 kHz. The acquired values are imported into Matlab, where the sampling frequency and the number of samples are defined, to perform the processing through the SSWT, the function is called with the 'wsst' command. In figures 9b to 9c the low resolutions in time and frequency are confirmed, unlike the SSWT, demonstrating its high effectiveness in non-stationary signals.

VI. Conclusion

This study demonstrates the limitations of traditional methods for time-frequency analysis of non-stationary signals generated in renewable energy sources with the short-time Fourier Transform and the Continuous Wavelet Transform; considering systems based on solar panels as wind generators before the evaluation in the power quality and the growing increase in modern power systems.

The Wavelet Syncrosqueezing Transform turns out to be a reliable and effective method for the analysis of harmonic and interharmonic content in AC/DC links, demonstrating a wide frequency and time resolution even in oscillatory signals with a smaller relative error.

The algorithm is applicable to existing disturbances in the electrical network due to other effects considered, such as the flicker effect, being the reconstruction of the signal from the CWT the frequencies extracted one of the main virtues to show a better resolution.

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