PERFORMANCE STUDY OF VARIABLE SHORT-TIME FOURIER FOR TRANSIENT DETECTION IN POWER SYSTEMS

Fernando Luis Dias[1] – fernandodias@unipampa.edu.br
Thiago Carvalho Rego[2] – thiago@hotmail.com.tr
Francine de Almeida Kalas[3] – francine_kalas@hotmail.com
Vera Lucia Duarte Ferreira[4] – veraferreira@unipampa.edu.br

[1,,3] Federal University Of Pampa– Bagé, RS, Brazil
[2] Energy Eng. Alumnus Federal University Of Pampa – Bagé, RS, Brazil
[4] University of State of Rio de Janeiro, Polytechnic Institute. Nova Friburgo, RJ, Brazil

Abstract. *This paper investigates the efficiency of time-frequency analysis in locating transients in power systems signals. Two experimental cases were simulated by the Matlab software. The first case is a linear system and the second is a three-phase synchronous generator. The transient analysis was performed by a Fourier technique called variable short-time Fourier transform, which uses a varying window size over time that is adjusted by local kurtosis given by the fourth normalized cumulant. The results obtained have evidenced the changes in frequency regime in both cases. The kurtosis defined by the fourth normalized cumulant effectively captures the nonlinearities present in both scenarios. The technique used proved to be able to identify and classify transients over time.*

Keywords: *High-order statistcs, Local kurtosis, Transients, Time-frequency mapping*

1. INTRODUCTION

In the last decades, the diversification of the energy matrix, in addition with the cities growth consumption, has as a consequence, an increase in the power systems operational complexity. Thus, it is necessary the modernization of the electric sector.

The electric sector expansion makes it more prone to failures, deviations or oscillations, and lead to a further degradation of the Electric Power Quality (EPQ) indices. In order to maintain the quality goals established by the regulatory agencies, it is indispensable to reduce the risks arising from the occurrence of power grid failures. Moreover, it is essential to detect the presence of disturbances, especially those caused by transients. In a short circuit for example, it can be generated a large increase of current in a fault area of the system. Thus, the accumulation of transients becomes a great threat (Song *et al.*, 2013). Transient disturbances have non-permanent characteristics, random occurrence, and high frequency index (Ferrero & Salicone, 2006).

Among the new methodologies in the transient detection in signals, those that use a window function support have received great attention from research groups and companies in the electric sector. The Short-Time Fourier Transform (STFT) technique in particular, is a tool capable of mapping frequencies over time. It uses a fixed-window function that analyzes the stretch of a signal (Yeap *et al.*, 2016). However, due to the Heisenberg uncertainty principle, it should be noted that it is not possible to obtain a good resolution in both time and frequency domains (Gröchenig, 2001). Jones & Baraniuk (1992), in order to overcome this peculiarity, present a simple technique for adapting the time-frequency representations by parametric optimization dependent on the time of the concentration of the time-frequency representations.

Lee (2013) to bypass the high computational load of the window adjustment by Jones & Baraniuk (*op.cit*) proposed the window adjustment calculation based on the usual statistics kurtosis at the fourth-normalized moment. This scheme is called Variable Short-Time Fourier Transform (VSTFT). However, this kurtosis definition, even based on high order statistics (HOS), is not sufficient for the characterization of non-linear and non-Gaussian signals. A more effective strategy is to use kurtosis as the fourth-normalized cumulant, as presented by Dias (2014) to optimize the Gaussian window function support (size) and center. In addition, high kurtosis means that the variance is due to infrequent extreme deviations, as opposed to frequent small sized deviations as exposed by Sharma *et al.* (2009). Therefore, in this paper, is proposed a simple and efficient technique for the continuous adaptation of the time-frequency representation. The method calculates a short-term quality measure of the representation for a range of values of a free parameter, maximizing the quality measure through interpolation.

2. EASE OF USE

2.1 Short-Time Fourier Transform Definition

For a given signal *s(t),* where w ≠ 0 is a window function, then the STFT $S_m(w)$ is defined as:

$$S_m(t_{fix}, f) = \sum_{n=-\infty}^{\infty} s(t) w(t - t_{fix}) e^{-j2\pi ft} \tag{1}$$

where t_{fix} is a fixed time delay, defined as

$$t_{fix} = t_s N_{fix} \tag{2}$$

with t_s is the sampling time and N_{fix} is a fixed window length.

In addition, *w(t)* is a generalized Gaussian window function defined by Lee (*op.cit*) as:

$$w(t, \alpha) = \frac{\alpha}{2\beta\tau\left(\frac{1}{\alpha}\right)} ^{-\left(\frac{-1}{\beta}\right)^{\alpha}} \qquad for \quad t < 0 \tag{3}$$

$$w(t, \alpha) = \frac{\alpha}{2\beta\tau\left(\frac{1}{\alpha}\right)} ^{-\left(\frac{1}{\beta}\right)^{\alpha}} \qquad for \quad t > 0 \tag{4}$$

where α > 0, τ is the gamma function, and is given by:

$$\beta = \frac{\tau\left(\frac{1}{\alpha}\right)}{\tau\left(\frac{3}{\alpha}\right)^{1/2}} \tag{5}$$

2.2 Variable Short-Time Fourier Transform Definition

The basic idea of the VSTFT analysis is to adjust the time-frequency resolution according to the frequency content. For this, it is used an intrinsic parameter to the signal and made effective the scheme by the kernel optimization of the STFT window function. Therefore, the parameters used in the window function size are defined throughout this section.

If S is a random variable, with the second and fourth finite central moments, then the kurtosis of a probability distribution $K[S]$ is given by:

$$\mathrm{K}[\mathrm{S}] = \frac{\mathrm{E}(\mathrm{S} - ES)^4}{\left(\mathrm{E}(\mathrm{S} - ES)^2\right)^2} \tag{6}$$

where E is the expected value.

However, because the definition of kurtosis given by Lee (*op.cit*) is based on the fourth-order moment, its generalized correspondent based on the fourth-order c_4 cumulant is given by

$$K = \frac{c_4(\mathrm{S})}{\left(\mu^2\right)^2} \tag{7}$$

where μ is the mean.

In this manner, the local kurtosis K_{local} is given by:

$$\mathrm{K}_{local}[\mathrm{S}_\mathrm{m}] = \frac{c_4(\mathrm{S}_\mathrm{m}(\mathrm{t},\mathrm{f}))}{\left(\mathrm{E}\left(\mathrm{S}_\mathrm{m}(\mathrm{t},\mathrm{f})\right)^2\right)^2} \tag{8}$$

It is important to note that the denomination of local kurtosis is such, because the STFT is also a local Fourier transform. In this way, the size of the K_{local} is defined as the Eq. (9):

$$\mathrm{N}_{local} = N_{max}\frac{\mathrm{K}_{local}}{\mathrm{K}_{\max}} \tag{9}$$

where N_{max} is the maximum pre-defined variable window size and K_{max} is the maximum kurtosis value.

The definition of the VSTFT requires that the resolution of the time and frequency stay connected to the kurtosis, thus the VSTFT S_{vm} is defined as

$$S_{vm}(t_{local}, f) = \int_{-\infty}^{\infty} s(t)w(t - t_{local})e^{-2\pi ift}\, dt \tag{10}$$

with

$$t_{local} = t_{\alpha}(N_{local}) \tag{11}$$

where t_{local} is a dislocation in time.

3. TRANSIENT SIMULATION

In this paper is presented the computational simulation of two well-known systems: a linear circuit perturbed by a transient (Mathworks, 2018), and a three-phase synchronous generator disturbed by a short-circuit proposed by Saadat (1998). These systems were chosen to be analyzed because of their didacticism.

The experimental signals in the first case are generated from a linear circuit of a simplified three-phase power system. The circuit contains an equivalent voltage source of 132.8kV RMS, and frequency of 60Hz and has an internal impedance in series. A RL load is fed by the voltage source through a 150 km transmission line that is modeled by an RL branch and two shunt capacitors also known as PI section. The transient occurs when a circuit breaker switches the load of 75 MW, and 20 Mvar at the end of the transmission line (Mathworks, *op cit.*). The transient can be observed in both current and voltage signals when the load is first switched off at t = 0.0333 s (2 cycles) and switched on again at t = 0.1167 s (7 cycles) as shown in Fig. 1. This experiment can be accessed in the software Matlab using the *power_transient* command. Simulink is a computational tool composed of a block library integrated to Matlab and widely used in dynamic system modeling (Pinheiro, 2012).

In the second case, the signals acquisition was based on the example 8.2 in Saadat (*op.cit.*). The studied system consists of a synchronous generator with a constant excitation voltage of 400 V operating at no-load. The disturbance is caused by a three-phase short circuit at the armature terminals at the instant when $\delta = 0$.

In Fig. 2, is observed that the phase currents i_a, i_b and i_c and the field current i_F consists of *dc* and *ac* components in which the *ac* component is decaying. Additionally, besides the fundamental frequency the *ac* component is also comprised by the second harmonic.

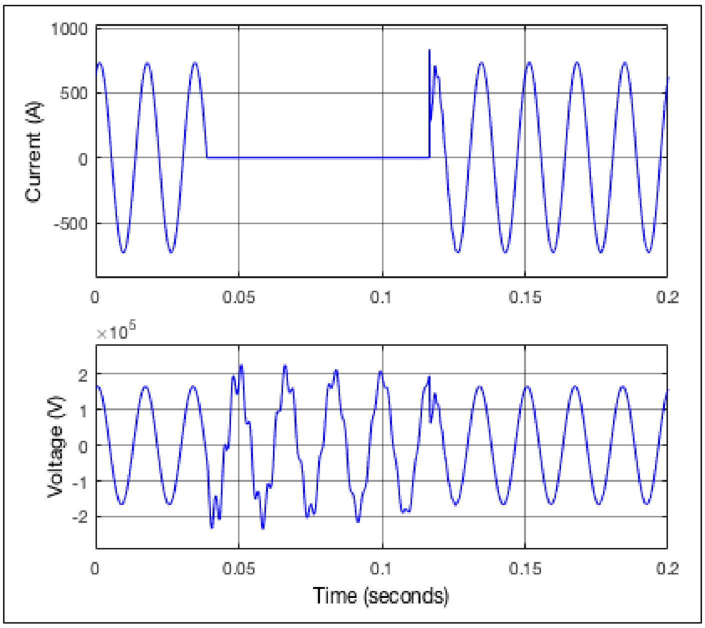

Figure 1- Current and voltage signal with transient caused by a breaker in a linear circuit.

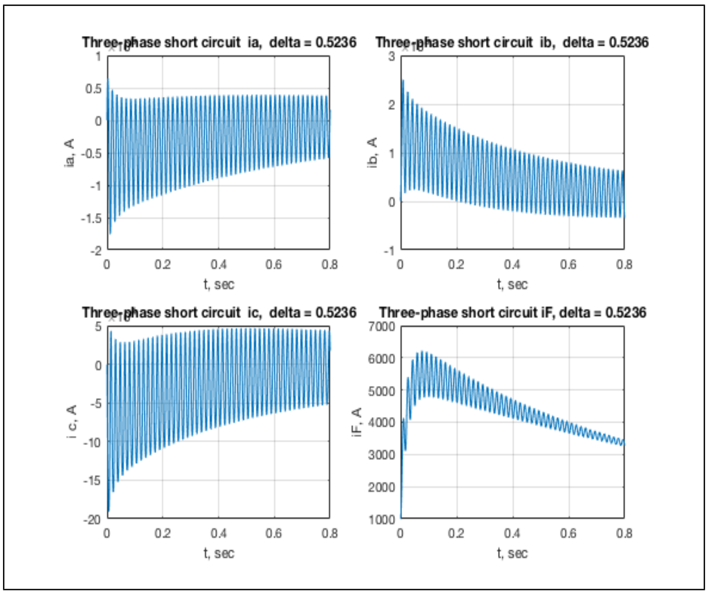

Figure 2- Balance short circuit phase (i_a,i_b and i_c) and field i_F currents waveforms.

4. PERFORMANCE TEST

As seen in the previous section, the signals studied here clearly show the points at which transient and / or harmonic disturbances occur. Thus, the VSTFT analysis aims to prove the already known data in order to demonstrate its efficiency in the detection of transients and harmonic disturbances in power systems.

4.1 Localization of transients

Statistical estimates of mean and variance are often used in real phenomena modeling under the hypothesis of randomness. However, this phenomenon is subject to the presence of deviations that induce transients that often are sufficient to induce long-tailed distributions to emerge, thus weakening the Gaussian assumption. Therefore, it is necessary to use statistical estimators of higher order than the second, for a better characterization of subjacent phenomena. This can be achieved by using non-robust estimators such as kurtosis.

At time intervals where the excess kurtosis is approximately zero, the probability density of the signal is close to the normal distribution. In this case, it is observed that when there is transitory change of the regime in the signal there will be variation of the local kurtosis.

Figs. 3-4 illustrate the local kurtosis profiles in the voltage and current signals in both linear system and synchronous machine analyzed in this paper respectively. It is noteworthy to observe that the variation of the steady state of the signal in the linear system is quite pronounced as seen in Fig. 3. The local kurtosis profile clearly shows the characteristic peaks of the perturbation applied at instants 0.0333 s and 0.1167 s.

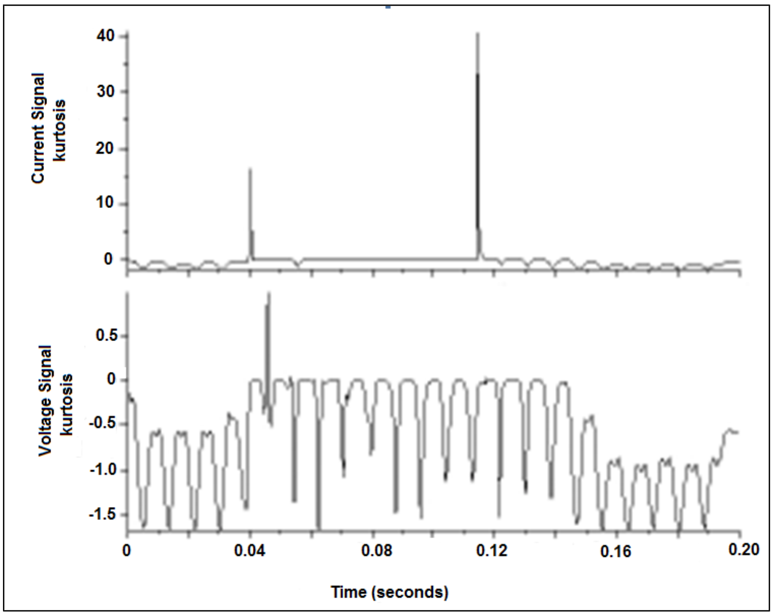

Figure 3- Kurtosis profile of current and voltage signals of the linear circuit.

In the short circuit case, on the other hand, the local kurtosis shows less pronounced variations, as can be seen in the profiles obtained for the i_a and i_b currents in Fig. 4A, and i_c and i_F in Fig. 4B. This is because the components of the second harmonic and stator currents are generally small. In addition, the ac components of the armature currents in Fig. 2, presents decay from a high initial value to a constant steady state value. This phenomenon can be observed through their respective kurtosis profiles. On the other hand, the current i_F raises its initial value in order to counterbalance the demagnetizing stator current. Thus, since the perturbations do not show large peaks, the local kurtosis profiles are more attenuated than the previous case.

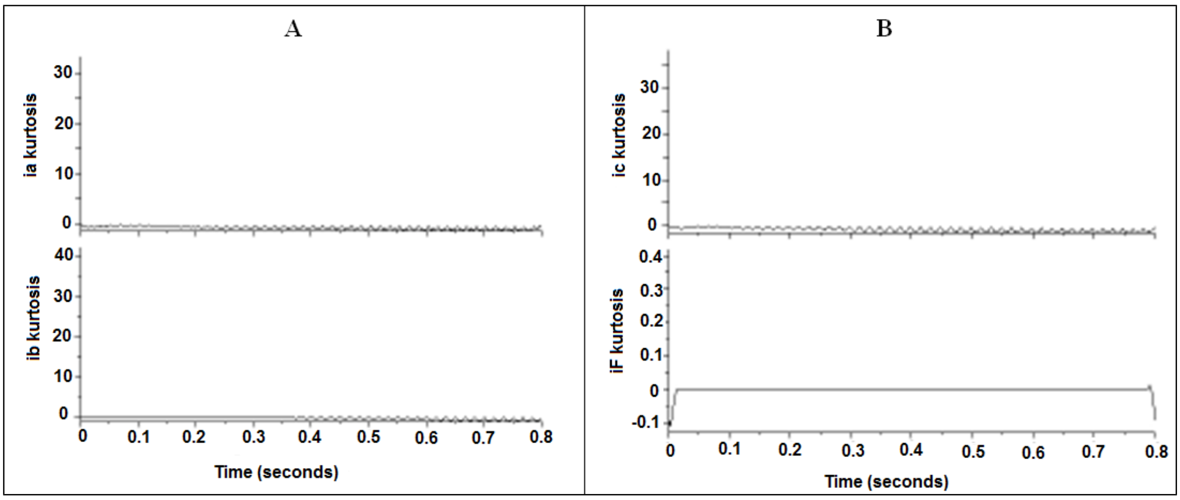

Figure 4- Kurtosis profile of the phase currents i_a , i_b (A), i_c and field current i_F (B)

4.2 Variable Short-Time Fourier Spectrogram

In this section is presented the time-frequency analyzes for both studied cases. Therefore, the spectral content mapping of the signals samples was screened in the time-frequency domain using the VSTFT.

By comparing the spectrograms of the signals presented in Fig. 5, it is clear that the kurtosis parameter defined by the fourth normalized cumulant captures more effectively nonlinearities, non-stationarity, and deviations of Gaussian behavior. This makes it possible to locate the instants in which the transients occur, as well as their length in time. The flexibility enabled the STFT to adjust the local characteristics of the signals in order to show the changes in frequency regimes, as can be seen in the 2D spectrograms shown in this section.

In Fig. 5A, that represents the current signal of the linear circuit, is observed a frequency lapse in the 0.0333 s and 0.1167 s intervals, provoked by the breaker inserted in the circuit. Thus, comparing the spectrogram in Fig. 5A and the current signal profile in Fig. 1, it can be seen that the frequency lapse occurs in the instant when the breaker is switched off and ends at the instant when it is switched on again, proving the efficiency of the time-frequency mapping in locating the transient. Also, note that the local kurtosis adjustments for the current signal in Fig. 3 influences directly in the VSTFT spectrum.

As shown in the Fig. 5B, the spectrogram as well as shown in Fig. 5A, illustrates the instants where the transient occurs. Note that because of the voltage behavior, the gaps in the frequency are not continuous as it is in the current. However, because both signals are related to each other, the frequencies should be the same. This can be seen in Fig. 5A and 5B that the frequencies on the spectrograms are the same, even thou their quantity of energy varies differently in each signal. Such phenomenon occurs because the behavior of the signals when the circuit breaker is switched off/on as seen in Fig 1.

The time-frequency mapping for the second case is illustrated in Fig. 6. Observe that the short-circuit causes different behavior in each current, as it was seen in Fig. 2. Differently from the previous circuit, the transient caused by a short-circuit in this scenario do not causes frequency lapses. In contrast, the elevation of the currents amplitude at the instant of the short-circuit generates a high frequency power that fades in time as the currents return to their steady-state. This behavior is illustrated in the spectrograms in Fig. 6A, 6B, 6C and 6D, respectively, for the phase currents i_a, i_b and i_c and the field current i_F. Note the spectrogram shown in Fig. 6D is in accordance with the expected frequency behavior for the i_F. This is, the concentration of energy in the frequency is higher since i_F adjusts itself to counterbalance the stator current.

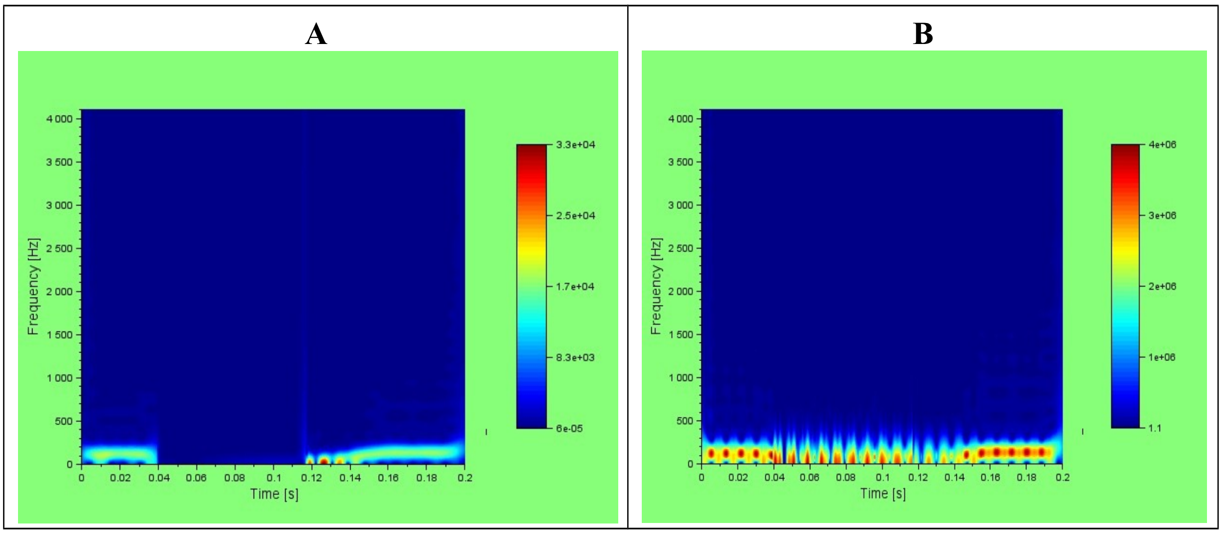

Figure 5- 2D spectrograms of the current signal (A) and voltage signal (B) of the linear circuit.

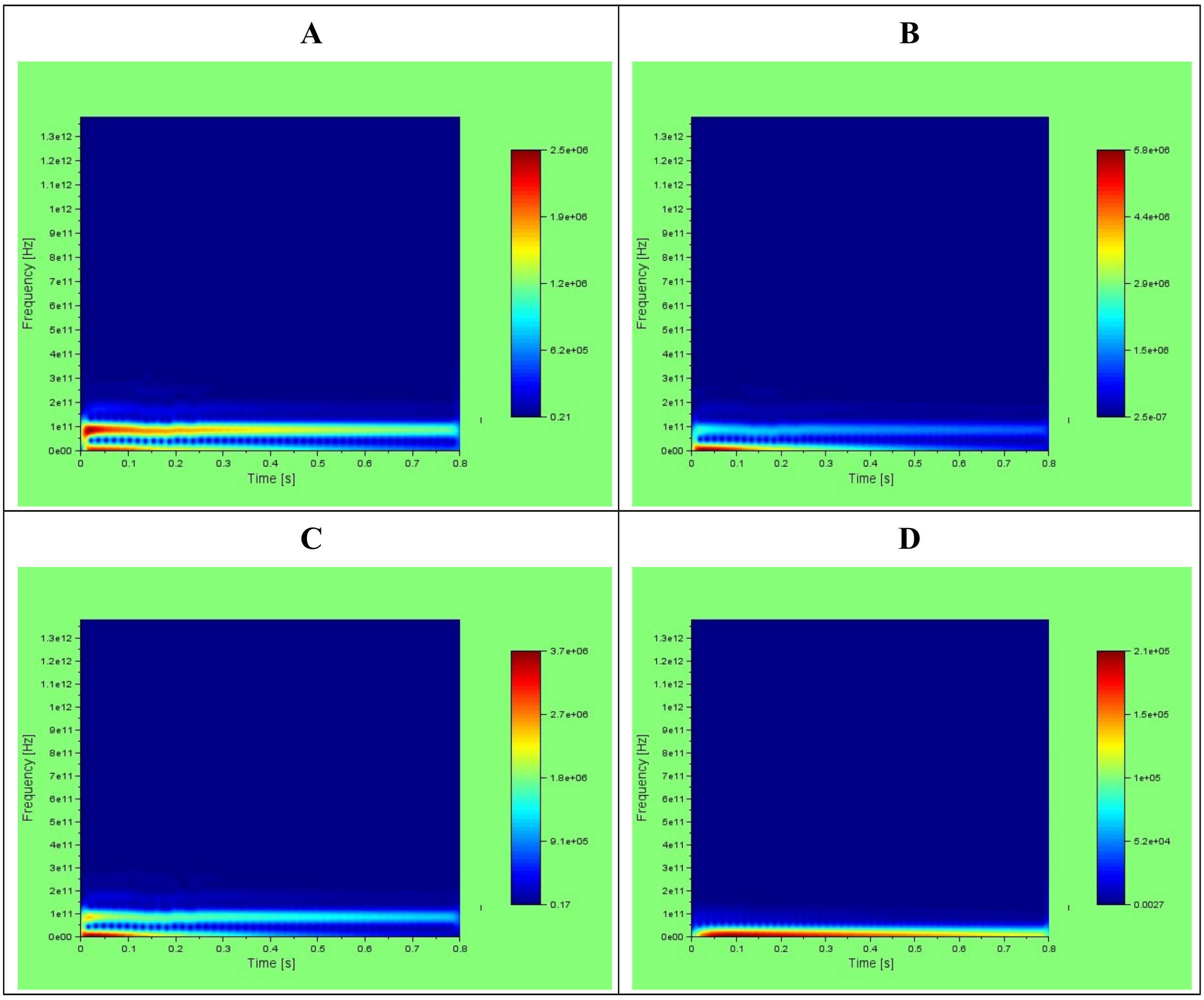

Figure 6- 2D spectrograms of the current signal i_a (A), i_b (B), i_c (C) and field current i_F (D) signal of the synchronous generator.

5. CONCLUSIONS

In this paper, a brief theoretical formulation on high-order statistics and time-frequency analysis using the local Fourier technique with a window function support adjusted by estimates of kurtosis defined by the fourth normalized cumulant were presented. Also, it was presented a study on the identification of transients for a simplified three-phase circuit (linear circuit) with a circuit breaker and a three-phase synchronous generator subject to short circuit disturbances at the terminals of its armature. The spectrograms and kurtosis profiles describe respectively, the temporal evolution of the spectrum and the detection of the transients, showing the efficiency in the use of HOS in the window size optimization, and consequently, the transient characteristics mapping.

REFERENCES

Song, X.; Sahinoglu, Z. & Guo, J. (2013) "Transient disturbance detection for power systems with a general likelihood ratio test," *Proc. of ICASSP*, Vancouver, Canada, 2839-2843.

Ferrero, A. & Salicone, S. (2006) "A method for testing instruments for transient detection in electric power system voltages" *Proc. of IMTC*, Sorrento, Italy, 1589-1591.

Yeap, Y., Ukil, A. & Geddada, N. (2016) "STFT analysis of high frequency components in transient signals in multi-terminal HVDC system," *Proc. of IECON*, Florence, Italy, 4008-4013.

Gröchenig, K. (2001) *Foundation of time-frequency analysis*. Springer.

Jones, D. & Baraniuk, R. (1992) "A simple scheme for adapting time-frequency representations," *Proc. IEEE-SP Int. Symp. Time-Scale Anal*, Sao Paulo, Brazil, 83-86.

Lee, J. (2013) "Kurtosis based time-frequency analysis scheme for stationary or non-stationary signals with transients," Information Technology Journal, vol. 12, 1394-1399.

Dias, F. (2014) "A local Fourier scheme to time-frequency analysis of nonstationary signals applied to electrochemical noise," P.h.d thesis, Polytechnic Institute, Rio de Janeiro State University, Nova Friburgo, Brazil.

Sharma, L.; Dandapat, S & Mahanta, A. (2009) "Kurtosis based multichannel ECG signal denoising and diagnostic distortion measures," *Proc. of TENCON*, Singapore, 1-5.

Mathworks (2018) "Introducing the phasor simulation method - MATLAB & Simulink," Available at: https://www.mathworks.com/help/physmod/sps/powersys/ug/introducing-the-phasor-simulation-method.html?searchHighlight=power_transient&s_tid=doc_srchtitle, [Accessed Jan. 8, 2018].

Saadat, H. (1998) *Power system analysis*. McGraw-Hill College, 327-329.

Pinheiro, C.I.C. (2012). *Tutorial de Introdução ao Simulink (versão 7.6).* Departamento de Eng. Química e Biológica. Instituto Superior Técnico. Lisboa.