Signal-Tuned Gabor Application in Islanding Detection in Distributed Generation at the Power System

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***Abstract*—The Signal-Tuned Gabor transforms are variant Gabor transforms based on temporal or spectral kernels whose parameters are defined, respectively, by the Fourier and inverse Fourier transforms of the analyzed signal. This yields time frequency transforms which are tuned to the specific features of their inputs, thus allowing analysis with high conjoint spectro-temporal resolution. Here we investigate the use of the signal-tuned Gabor transforms as tool for the Islanding Detection in Distributed Generation Systems. We show that the signal-tuned Gabor transform based on the spectral kernel yields higher-quality, more informative spectrograms, which are consistently superior to those afforded by the *S* transform.**

***Index Terms*—Gabor transform, Power quality, Signal-tuned Gabor approach,*S* transform, Time-frequency analysis, Islanding, Detection.**

I. Introduction

The growing use of distributed generation (DG) resources in distribution network provides many benefits in terms of high power quality, efficiency, and low carbon emissions in power system. However, efficient islanding detection and immediate disconnection of DG is critical in order to avoid equipment damage, grid protection interference, and personnel safety hazards. Signal processing techniques, in particular, are adopted due to their versatility, stability, cost effectiveness, and ease of modification. The methods of frequency analysis (TF) are very exploited, since traditional techniques such as Fast Fourier Transform (FFT), GT (Gabor Transformation), Stockwell Transform (ST) and Wavelet Transform (WT) are used for the recognition, classification and detection of disturbances [1] - [6]. Here we will consider the use of a new time-frequency approach - the signal-tuned Gabor transforms. The original signal-tuned approach was proposed as a means of tailoring the Gabor transform to each input signal, such as to allow the accurate conjoint detection of its temporal and spectral events [7],[8]. To this end, the width and the phase of the Gabor analyzing kernels have been defined based on the magnitude and phase of the signal's Fourier transform. With such a choice, the transient features of the input signal, which tend to be associated with smaller Fourier magnitudes, are analyzed by short-scale Gabor kernels, while shortbandwidth kernels analyze the signal's stationary components. This allows tracking of the transient signal features with high temporal resolution, while keeping higher frequency resolution for the signal's dominant spectral components. In [7], the possibility of an alternate form of the signal-tuned transform was also indicated, whereby the input signal's Fourier transform is probed with Gabor spectral kernels whose width and phase are based on the temporal signal's magnitude and phase. In this case, higher-amplitude temporal events will be analyzed with higher temporal resolution, while higher spectral resolution is employed for the lower-amplitude components. In the islanding detection in distributed Generation Systems application considered here, our results show that the signal-tuned Gabor transform based on the spectral kernel yields higher-quality spectrograms, those afforded by the widely used S transform. This paper is organized as follows: in sections II and III we show the definitions of the TF transforms used for analysis, in section IV we present the application of islanding detection in distributed generation systems and simulations. Lastly, conclusions are drawn from the studies in Section V.

II. Time-Frequency Transforms

Time-frequency approaches are a standard tool for power-quality analysis, the Gabor and S transforms, and also the Wigner transform, being commonly used for the detection and classification of signal disturbances [4]. The Gabor transform of a signal $x(t)$ corresponds to its short-time Fourier transform under a Gaussian window – or, equivalently, to its analysis by a Gabor kernel (a Gaussian-modulated complex exponential). It takes the form

$$G(t,\omega) = \int_{-\infty}^{+\infty} e^{-i\omega\tau} e^{-\frac{(\tau-t)^2}{2\sigma^2}} x(\tau) d\tau \tag{1}$$

where σ, the Gaussian width, is a fixed parameter which must be empirically chosen.

The S transform was proposed by Stockwell and collaborators, as a means of combining positive features of the Gabor and wavelet transforms [5]. It is defined as

$$S(t,\omega) = \frac{|\omega|}{(2\pi)^{3/2}} \int_{-\infty}^{+\infty} e^{-i\omega\tau} e^{-\frac{(\tau-t)^2\omega^2}{2(2\pi)^2}} x(\tau) d\tau \qquad (2)$$

and thus corresponds to a short-time Fourier transform under a Gaussian window whose width varies inversely with the frequency, such that the high-frequency components of the input will be probed with greater temporal resolution. Thus, similarly as the wavelet transform, the S transform is able to "zoom-in" on the fine temporal details of the analyzed signal, but at the cost of losing spectral resolution at the higher frequencies.

An alternative approach to time-frequency analysis is based on Wigner's quasi-probability distribution, originally introduced in quantum physics. The Wigner or Wigner-Ville transform uses the input signal itself as analyzing kernel. It is a real transform, and displays several properties which make it ideal as an analysis tool, but, on the other hand, being a bilinear transform, it suffers from the so-called cross-term problem, which leads to the appearance of spurious terms in the frequency spectra of multi-component signals [4]-[6].

III. Signal-Tuned Gabor Transforms

The signal-tuned Gabor transform (STGT) was originally proposed in [7] and [8] as a variant Gabor transform whose analyzing kernel has its parameters determined by the Fourier magnitude and phase of the analyzed signal – the former defining the kernel's width, while the latter defines its phase. The STGT thus takes the form

$$T(t,\omega) = \frac{1}{(2\pi)^{3/2}} \int_{-\infty}^{+\infty} e^{-i[\omega\tau+\varphi(\omega)]} e^{-\frac{(\tau-t)^2}{2|X(\omega)|^2}} x(\tau)\, d\tau \qquad (3)$$

with $|X(\omega)|$ and $\varphi(\omega)$ denoting, respectively, the magnitude and the phase of the Fourier transform of the analyzed signal – i.e., $\mathcal{F}_{t\to\omega}\{x(t)\} = |X(\omega)|e^{i\varphi(\omega)}$ –, where $\mathcal{F}_{t\to\omega}\{x(t)\} = X(\omega)$ is the Fourier transform of $x(t)$, here defined as $X(\omega) = \int e^{-i\omega t}x(t)dt$.

The set of STGT kernels,

$$\psi_\omega(t) = \frac{1}{(2\pi)^{3/2}} e^{i[\omega t+\varphi(\omega)]} e^{-\frac{t^2}{2|X(\omega)|^2}} \qquad (4)$$

for all possible ω values, has been shown to allow the exact representation of the signal $x(t)$, under the form

$$x(t) = \int_{-\infty}^{+\infty} e^{i\omega t} < \psi_\omega(t), e^{i\omega t} > d\omega \qquad (5)$$

where the brackets denote a temporal inner product – i.e., $< f(t), g(t) >= \int_{-\infty}^{+\infty} f(\tau)g^*(\tau)d\tau$, with $g^*(\tau)$ being the complex conjugate of $g(\tau)$. From Eq. (5) we conclude that, insofar as the frequency ω is concerned, the kernel $\psi_\omega(t)$ is equivalent to the signal $x(t)$, and will therefore be referred to as a *coding function* of $x(t)$. The STGT thus amounts to the analysis of the given signal by its own coding functions, what lends the transform some of the ideal analytic properties of the Wigner transform – for instance, the projection property along the t dimension, which yields the signal's power spectrum as

$$|X(\omega)|^2 = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\infty} T(t,\omega)dt \qquad (6)$$

Moreover, the STGT adapts to the analysis of each given input, displaying a "zooming-in' property similar to that of the wavelet transform, but in a signal-specific way, as it tracks the transient features of the signal – typically associated with smaller Fourier magnitudes – with shorter temporal-scale, and thus larger spectral-bandwidth Gabor functions, while using larger-scale, smaller-bandwidth kernels to probe the signal's stationary features, typically associated with larger Fourier magnitudes. As illustrated in [7] through the analysis of electroencefalographic traces, this allows the precise detection of a signal's events in situations where traditional approaches – such as the standard Gabor or S transforms – tend to fail.

A second version of the signal-tuned Gabor transform – which will be referred to as the STGT_2 – has been introduced in [9], based on analyzing kernels of the form

$$\psi_t(\omega) = \frac{1}{(2\pi)^2} e^{-i[\omega t-\phi(t)]} e^{-\frac{\omega^2}{16\pi^3|x(t)|^2}} \qquad (7)$$

where $x(t) = |x(t)|e^{i\phi(t)}$ is the complex temporal signal whose Fourier transform is $X(\omega)$ – i.e., $\mathcal{F}^{-1}_{\omega\to t}\{X(\omega)\} = |x(t)|e^{i\phi(t)}$, where the inverse Fourier transform is here defined as $x(t) = (2\pi)^{-1}\int e^{i\omega t}X(\omega)d\omega$. A signal-tuned Gabor transform can thus be defined whereby the spectral signal $X(\omega)$ is probed with the kernels $\psi_t(\omega)$, i.e.,

$$T_2(t,\omega) = \frac{1}{(2\pi)^2} \int_{-\infty}^{+\infty} e^{i[\Omega t-\phi(t)]} e^{-\frac{(\Omega-\omega)^2}{16\pi^3|x(t)|^2}} X(\Omega)d\Omega \qquad (8)$$

The set of $\psi_t(\omega)$ kernels for all possible t values yields an exact representation of the spectral signal $X(\omega)$, as

$$X(\omega) = \int_{-\infty}^{+\infty} e^{-i\omega t} < \psi_t(\omega), e^{-i\omega t} > dt \qquad (9)$$

where the brackets here denote a spectral inner product: $< F(\omega), G(\omega) >= \int_{-\infty}^{+\infty} F(\Omega)G^*(\Omega)d\Omega$, $G^*(\Omega)$ being the complex conjugate of $G(\Omega)$. From Eq. (9) we conclude that, at time t, the kernel $\psi_t(\omega)$ is equivalent to $X(\omega)$, and can therefore be referred to as a coding function of $X(\omega)$. The STGT_2 thus amounts to the analysis of a spectral signal by means of its own coding functions, what lends it some of the properties of the Wigner transform which are not shared by the STGT, such as allowing recovery of the signal's power spectrum through a projection along the frequency dimension:

$$|x(t)|^2 = \frac{1}{2\pi} \int_{-\infty}^{\infty} T_2(t, \omega) d\omega \tag{10}$$

Similarly as the STGT, the STGT$_2$ adapts to each analyzed signal, probing its higher-amplitude portions with shorter-temporal, and thus larger spectral-bandwidth Gabor kernels, while using larger-scale, smaller-bandwidth kernels to analyze the signal's low-amplitude portions.

In [8], the signal-tuned Gabor functions and transforms have been shown able to provide a suitable model for certain types of cells of the primary visual cortex, in the sense of replicating their responses to standard inputs, and also of mimicking the stimulus-dependent character of their receptive field functions. More specifically, the coding functions $\psi_\omega(t)$ and the associated transform $T(t, \omega)$ have been shown to model, respectively, the receptive fields and the responses of the so-called *complex* cortical cells, while the coding functions $\psi_t(\omega)$ and the transform $T_2(t, \omega)$ will do the same for the so-called *simple* cortical cells. Even though such results lend biological support to both signal-tuned approaches, the relevance of the STGT$_2$ as a signal-analysis tool still lacked a concrete demonstration. Here we will show that, owing to its specific characteristic of distinguishing the spectro-temporal signatures of the higher- and lower-amplitude segments of a given input, the STGT$_2$ provides a particularly suitable means for the analysis of power-signal disturbances.

IV. APPLICATION: ISLANDING DETECTION IN DISTRIBUTED GENERATION SYSTEMS

The recourse to distributed generation systems has become a growing trend in recent years, but the connection of such a system to a distribution network must be closely monitored, in order to avoid disruption of the network's performance, and even potential risks to its physical integrity. An important monitoring operation is the detection of islanding, which may occur when part of the utility grid is abruptly shut down, while other portions continue to be fed by local generators [10] - [16]. Here we present a study of the signal-tuned Gabor approach in islanding detection experiments based on a simulated system whose simplified model appears in Fig.1. The system has been designed with MATLAB's SimPowerSystems toolbox [14], and corresponds to a 29-bus electric network including hydraulic, biomass, solar and eolic generation (see figure caption for details).

The methodology used to islanding detection proposed in papers [15] - [19] was used in this paper, that is, by the calculation of the Standard deviation and also the calculation of the energy content (Parseval's theorem) of the matrix TF. Initially, the voltage signal samples retrieved at the target DG locations are processed through Time-Frequency Transforms that generate the matrix and the corresponding time-frequency contours. The time-frequency contours generated after pre-processing the voltage signals localize the islanding events effectively. Further to track the islanding events, the spectral energy content of the time-frequency contours of the voltage signals are calculated, and corresponding energy index is computed. The spectral energy of the time-frequency contours contains the information on frequency and magnitude deviations, which are the prime considerations for islanding detection process in distributed generations.

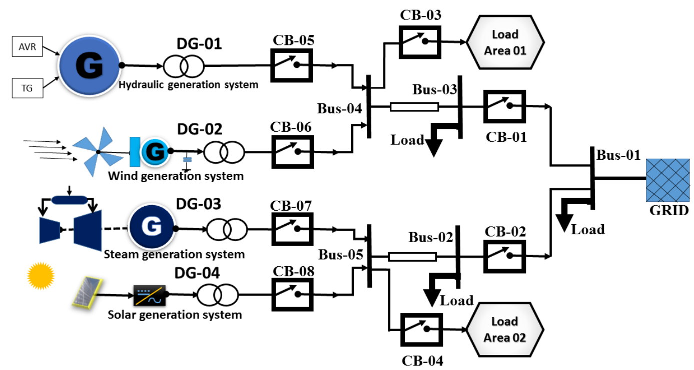


Fig. 1. Model of a hybrid distributed-generation system. DG-01 to DG-04 represent different distributed-generation sources, while CB-1 to CB-8 are circuit breakers. The main loads are connected to the sources via Bus-04 and Bus-05.

1) Islanding Simulation - Short Circuit: We have simulated a three-phase short circuit at Bus-02, lasting for 15ms. This entails the opening of circuit breaker CB-01 and, as a result, the voltage at Bus-04 falls abruptly, oscillates, and then overshoots (see Fig. 2(a)). With the coming into operation of the voltage regulators, the signal finally stabilizes at around 1.38 p.u. The total simulation time was 1s, corresponding to 3500 samples, with the disturbance taking place at 0.45s, corresponding to 1500 samples.

Figs.2(b) and (c) present the signal-tuned STGT and STGT2 spectrograms of the voltage signal in Fig.2(a), with Fig.2(d) also displaying, for comparison, the S-transform spectrogram. It is apparent that both signal-tuned approaches are able to detect the onset of the disturbance with higher accuracy than the S transform.

2) Islanding Simulation - Load Rejection: Load rejection is a technical maneuver which consists in the progressive elimination of a set of loads, so as to allow the system, under unusual operating circumstances, to return to appropriate levels of voltage and frequency. We have simulated the opening of circuit breaker CB-03, entailing load rejection in Area 1. As shown in Fig.3(a), there is a sudden voltage surge in Bus-04 and, after some transient oscillation, the signal stabilizes around 1.40 p.u. Figs.3(b) to 3(d) present the signal-tuned and S-transform spectrograms of the voltage signal in Fig.3(a). Again,

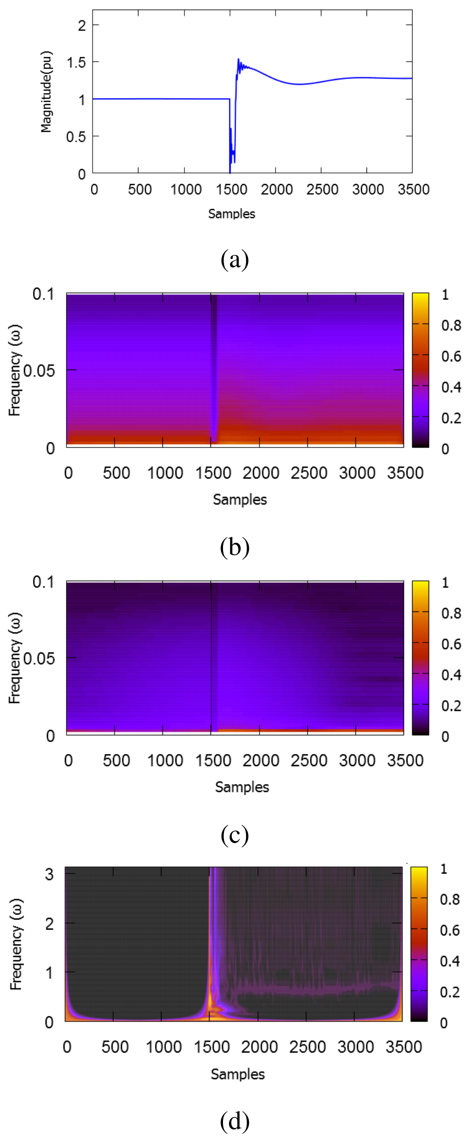


Fig. 2. Detection of islanding by short circuit: (a) Voltage at Bus-02, (b) STGT spectrogram, (c) $STGT_2$ spectrogram, (d) S-Transform spectrogram.

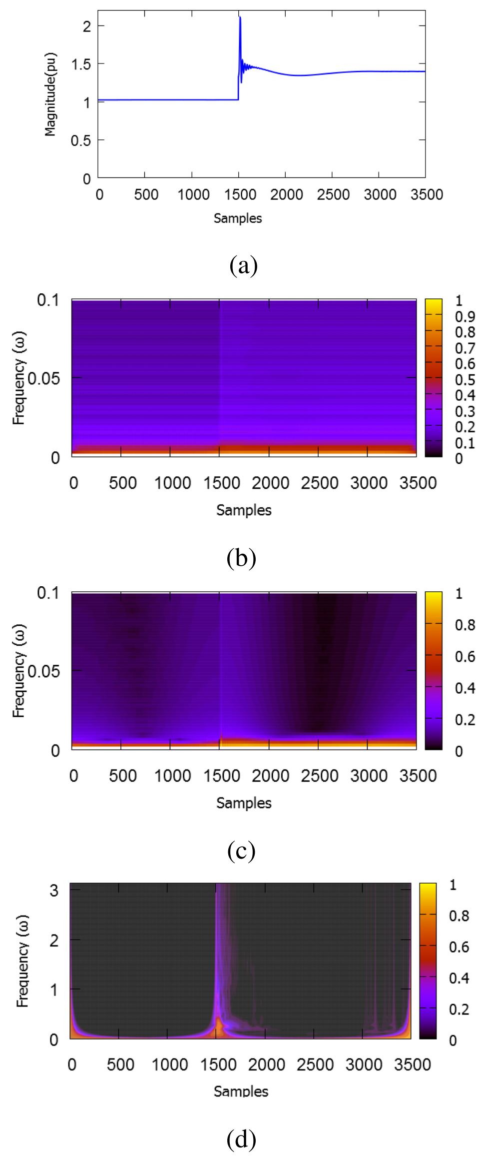


Fig. 3. Detection of islanding by load rejection: (a) Voltage at Bus-04, (b) STGT spectrogram, (c) $STGT_2$ spectrogram, (d) S-Transform spectrogram.

both signal-tuned approaches are able to detect the beginning of the disturbance with greater accuracy than the S transform, with the voltage surge giving rise, in this case, to a sharper STGT signature, due to the STGT2 tendency to replicate the signal's temporal oscillations.

Table 01 and 02 present the values of the deviation calculation Standard and the Energetic content of the matrix time frequency of the events studied, the values presented in the column "normal operation" serve as reference to compare with the values obtained in the occurrence of the islanding, as cited in references [16] to [19].

The graphical analysis of the Figs. 2 and Fig. 3 demonstrate

TABLE I
DETECTION OF ISLANDING BY SHORT CIRCUIT

TF	Normal Operation		Islanding	
	STD	Energy	STD	Energy
STGT	219E-04	5,018E-04	263E-04	7,038E-04
$STGT_2$	306E-04	9,396E-04	327E-04	11E-04
ST	551E-04	31E-04	701E-04	51E-04

TABLE II
DETECTION OF ISLANDING BY LOAD REJECTION

TF	Normal Operation		Islanding	
	STD	Energy	STD	Energy
STGT	219E-04	5,018E-04	244E-04	6,017E-04
$STGT_2$	306E-04	9,396E-04	346E-04	12E-04
ST	551E-04	31E-04	555E-04	32E-04

clearly the detection of the islanding event using the three methods: STGT, $STGT_2$ and ST transformations, and also emphasize the details of the beginning of the islanding obtained by the STGT and $STGT_2$ transforms (in 1550 samples). It is found that the resolution or the definition of the instant of the occurrence of the disturbance is precise with the use of STGT and $STGT_2$, Figs. 2(b), 2(c) and Figs. 3(b), 2(c), unlike ST Figs. 2(d) and Fig. 3(d)

The detection sensitivity of the transforms is verified. It is observed in the values of standard deviation and energy that the STGT and $STGT_2$ obtained satisfactory values, which are very different of normal operating values, energy content of the time-frequency transform such with STGT and $STGT_2$ is proposed. An energy index is computed using the spectral energy content of the voltage signals, which detects the islanding conditions effectively, as can be seen in the Figs.4 to Fig.7. The qualitative and quantitative data show the merits of the STGT and $STGT_2$, proposed for islanding detection in system with DG.

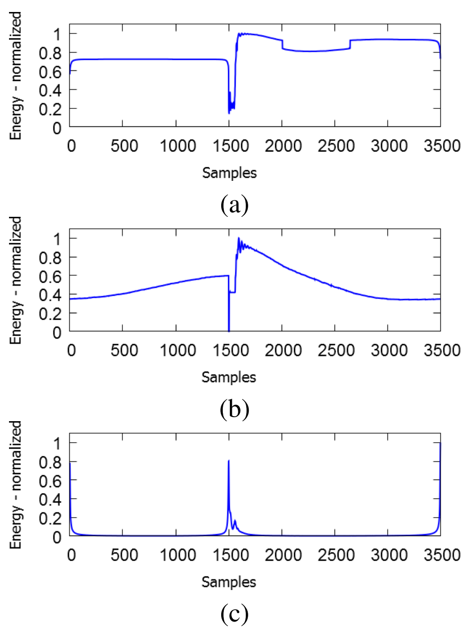


Fig. 4. Detection of islanding by short circuit obtained in the selected TF-matrix: (a) Energy detection-STGT, (b) Energy detection-$STGT_2$, (c) Energy detection-ST.

V. Conclusions

A new time-frequency analysis method called $STGT_2$ is proposed for islanding detection, using Gabor functions whose parameters are obtained from the Fourier transform, in these, each signal – spatial or frequency – is analyzed by Gabor nuclei associated with their own representation, so that the signal itself is its analyzing function. The method improves resolution over time and also frequency resolutions simultaneously, solves the problem of the ST low resolution. It is known that the width of the window is critical for TF analysis, where the use of a

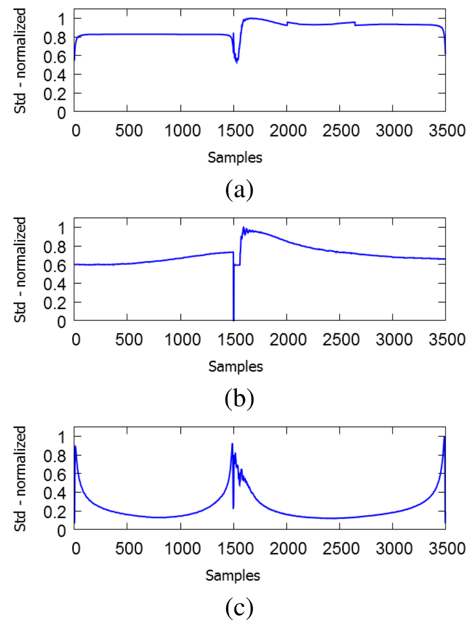


Fig. 5. Detection of islanding by short circuit obtained in the selected TF-matrix: (a) standard deviation detection-STGT, (b) standard deviation detection-$STGT_2$, (c) standard deviation detection-ST.

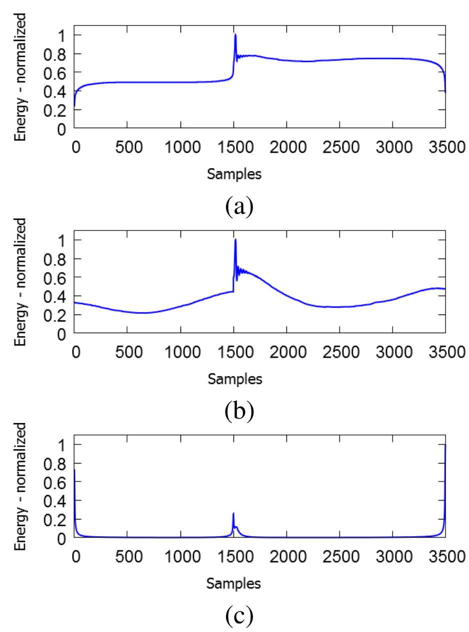
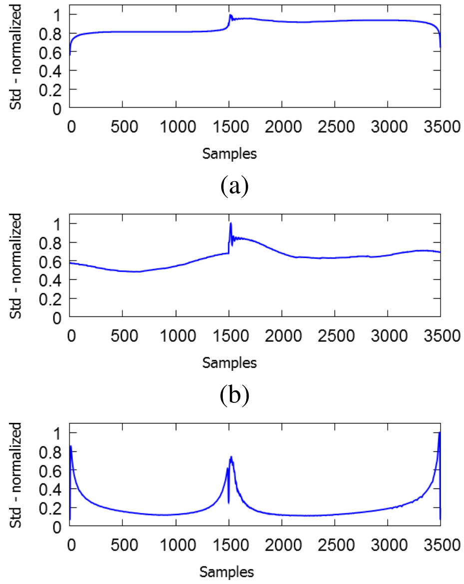


Fig. 6. Detection of islanding by load rejection obtained in the selected TF-matrix: (a) Energy detection-STGT, (b) Energy detection-$STGT_2$, (c) Energy detection-ST.



(a)

(b)

(c)

Fig. 7. Detection of islanding by load rejection obtained in the selected TF-matrix: (a) standard deviation detection-STGT, (b) standard deviation detection-STGT_2, (c) standard deviation detection-ST.

larger window of time detects slow changes and since a smaller window detects fast changes of frequency, the tuned transforms STGT and STGT_2 behaves very well in relation to this in the analyzed disturbance.

In order to evaluate the performance of the detection, the calculation of the energy content and the standard deviation of the TF matrix of each transform were also performed in terms of indices, from which the graphs of these values were also generated, the quantitative results show the sensitivity of the transformed tunes in detecting variations of this type of disorder, the promising superiority of the STGT_2 for the detection and location of islanding occurred in DG systems has been confirmed.

It should be noted that, unlike papers [16] to [19]. in this case study the objective is to propose a new tool which, compared with other results, is satisfactory or even better in detection applications, due to resolution and precise detection. The proposed method proves to be effective for analyzing and detecting signals in SEP islanding, with the STGT_2 being compared to the traditional ST, and evaluated as a promising tool for the analysis of electrical disturbances.

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