COMPARISON BETWEEN WAVELET AND FOURIER-BASED FREQUENCY ESTIMATION IN MICROGRIDS

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Abstract— An electric power system must operate with a constant frequency. However, frequency variations may occur in the system due to variations in loads, switching operations, disconnections and connections of generators, faults, etc. Distributed generation (DG) systems are subject to frequency variations, due to its characteristic of non-dispachability of power, that may cause various problems in the grid. In order to identify the frequency variation problem present in DG systems, this paper is present a comparison between two frequency estimation techniques, one based on the Continuous Wavelet Transform and the other based on the Short Time Fourier Transform, which has a good resolution time and frequency. The two techniques were compared under different conditions to analyse their performance in a microgrid connected to the network, with two DG systems, a photovoltaic system and a generation with synchronous machine.

Keywords— Microgrid, frequency estimation, Fourier transform and wavelet transform.

Resumo— Um sistema elétrico de potência deve operar com uma frequência constante. No entanto, podem ocorrer variações na frequência do sistema devido a mudanças nas cargas, operações de comutação, desconexões e conexões de geradores, faltas elétricas, etc. Os sistemas de geração distribuída (GD) estão sujeitos a variações de frequência devido à sua característica não despachável de energia, que pode provocar vários problemas na rede. Para identificar o problema de variação de frequência presente nos sistemas com GD, este trabalho apresenta uma comparação entre duas técnicas de estimativa de frequência, uma baseada na Tranformada Wavelet Contínua e outra baseada na Short Time Fourier Transform, que possuem uma boa resolução no tempo e na frequência. As duas técnicas foram comparadas em diferentes condições para analisar seu desempenho em uma *microgrid* conectada à rede, com dois sistemas de GD, um sistema fotovoltaico e uma geração com máquina síncrona.

Palavras-chave— Microgrid, estimação de frequência, transformada de Fourier e transformada wavelet.

1 Introduction

An electric power system must operate at its fundamental frequency ($f = 50$ or 60 Hz). However, small frequency variations are observed in the systems due to unbalance between the load and the power grid when changes occur in the system. According to the IEEE Standard 1159-2009 (IEEE 1159, 2009), frequency variations around ± 0.1 Hz are permissible for monitoring electric power quality, whereas in distributed generation (DG) systems the limit is ± 0.5 Hz (IEEE 1547, 2003). Therefore, frequency variations, which exceed the limits established by the standard can cause several problems such as disconnection of large loads, loss of synchronism in the machines, as well as their disconnection.

The increase in the amount of renewable resources and, consequently, the lower use of synchronous machines, leads to a decrease in rotational inertness in the electric energy system (Dehghanpour and Afsharnia, 2015). Therefore, increasing the magnitude of frequency shifts is predicted in energy systems with high penetration of renewable resources (Dehghanpour and Afsharnia, 2015). This new system configuration requires efficient and reliable frequency estimation for protection and control systems to operate quickly and correctly.

Protection systems must estimate the frequency of the grid, act, and disconnect at maximum 0.16 s when the estimated values goes beyond the thresholds, ±0.5 Hz to DG size less than 30 kW, established by the Standards. The under- and over-frequency relays are devices to protect the power electric systems against frequency variations. Several frequency-based methods for relays can be find in the literature, such as the well-known Rate of Change of Frequency (ROCOF) relay (Gupta et al., 2017; Vieira et al., 2006; Freitas et al., 2005; Khodaparastan et al., 2017; Affonso et al., 2005).

The frequency estimation methods have been performed in both time and frequency domains. The short time Fourier transform (STFT) has been widely applied to estimate grid frequency in power systems. The STFT provides both a high resolution in the time-frequency and a low computational burden (Bruno et al., 2006). As an advantage, the STFT adjust the time window so that to map the input signal in two dimensions: time and frequency. The STFT is more appropriated for the stationary signals analysis (Bruno et al., 2006). However, under non-stationary conditions and transients, the STFT-based methods can provide wrong results due to the abrupt variations of the signal, spectral leakage, and picket-fence effect (Bruno et al., 2006; Bronzini et al., 2007).

The continuous wavelet transform (CWT) is a mathematical tool for signal processing and analysis of nonstationary signals, which allows analyzing input signal in both time and frequency domains. The CWT provides an analysis of the signal in different scales, compressions, and shifts. Unlike the STFT, the CWT does not have a fixed time window. Therefore, the CWT has a variable width window, which can be properly adjusted according to the frequency range of interest (Addison, 2005).

This paper presents the comparison between two methods, CWT and STFT, for frequency estimation in a simulated low voltage (LV) microgrid system. The two methods are compared for different sampling frequency to demonstrate that the correct frequency estimation using the STFT method only occurs when the sampling frequency is multiple of the fundamental frequency, and there is no frequency deviation in the fundamental frequency, whereas the sampling frequency does not influence the frequency estimation of the CWT-based method.

2 Fourier Transform

The Fourier transform (FT) is a mathematical tool which has been widely employed in power system analysis due to its simplicity The FT of a continuous time function of an input signal $x(t)$ must attend to integrability conditions, as follow (Phadke and Thorp, 2008):

$$X(f) = \int_{-\infty}^{+\infty} x(t)e^{-j2\pi ft}dt, \tag{1}$$

and the inverse FT is defined as (Phadke and Thorp, 2008):

$$x(t) = \int_{-\infty}^{+\infty} X(f)e^{j2\pi ft}df. \tag{2}$$

Consider a discrete signal, $x(k\Delta t)$ where $k = 0, ..., N-1$ and Δt the sampling interval, with N samples in the data window T_0 (Phadke and Thorp, 2008):

$$A_n = \sum_{k=0}^{N-1} x(k\Delta t)e^{\frac{-j2\pi kn}{N}}, \tag{3}$$

where $n = 0, \pm 1, \pm 2, ...$ The relation between the Fourier series coefficients and DFT results in phasor representation of the kth harmonic component is given by (Phadke and Thorp, 2008):

$$X_k = \frac{\sqrt{2}}{N}\sum_{n=0}^{N-1} x(n\Delta t)\{\cos(\frac{2\pi kn}{N}) - j\sin(\frac{2\pi kn}{N})\}. \tag{4}$$

Consider θ as $2\pi/N$ and the notation $x_n = x(n\Delta t)$. Then, X_k will be (Phadke and Thorp, 2008):

$$X_k = \frac{\sqrt{2}}{N}\sum_{n=0}^{N-1} x_n\{\cos(kn\theta) - j\sin(kn\theta)\}. \tag{5}$$

Separating the terms, sine and cosine, of the Equation 5 (Phadke and Thorp, 2008):

$$X_{kc} = \frac{\sqrt{2}}{N}\sum_{n=0}^{N-1} x_n\cos(kn\theta), \tag{6}$$

$$X_{ks} = \frac{\sqrt{2}}{N}\sum_{n=0}^{N-1} x_n\sin(kn\theta). \tag{7}$$

Then, the phasor X_k is given by (Phadke and Thorp, 2008):

$$X_k = X_{kc} - jX_{ks} \tag{8}$$

According to the Heisenberg uncertainty principle, it is not possible to obtain a good resolution in time and frequency even if the STFT spectrometer it is used for time and frequency energy analysis (Lu and Zhang, 2009).

3 Continuous Wavelet Transform

The CWT allows to represent a signal in the time-frequency domain in the translated and dilated version of a mother wavelet $\phi(t)$. The CWT of a signal $x(t)$ is mathematically defined by means of the calculation of the wavelet coefficients $T(a,b)$ at different scales a and positions b (Addison, 2002; Farge, 1992; Büssow, 2007; Addison, 2005; Rueda et al., 2011).

$$T(a,b) = \frac{1}{\sqrt{a}}\int_{-\infty}^{+\infty} x(t)\phi^*(\frac{t-b}{a})dt, \tag{9}$$

where $\phi^*(t)$ represents the complex conjugate of the analyzing wavelet function $\phi(t)$, whereas $((t-b)/a)$ is associated the scale and time translated of the wavelet function and the term $1/\sqrt{a}$ is the normalization factor.

The wavelet function presents the following properties (Addison, 2002):

$$E = \int_{-\infty}^{+\infty} |\phi(t)|^2 dt < \infty, \tag{10}$$

$$\hat{\phi}(f) = \int_{-\infty}^{+\infty} \phi(t)e^{-i(2\pi f)t}dt, \tag{11}$$

$$C_g = \int_0^{+\infty} \frac{|\hat{\phi}|(t)}{f} df < \infty, \quad (12)$$

where the signal must have finite energy and zero frequency component.

The CWT can be used for frequency estimation with the appropriate choice of the mother wavelet (Avdaković et al., 2014). In the literature there are several wavelet functions, such as Morlet, Shannon, Mexican Hat, Meyer, Gabor, Gaussian, etc., which can be selected according to the nature of the signal to be analyzed (Bronzini et al., 2007). The complex Morlet wavelet is the most suitable for transient and non-stationary signals analysis due to the localized filters in the time-frequency domain (Rueda et al., 2011).

The complex Morlet wavelet is defined by (Rueda et al., 2011):

$$\phi(t) = \frac{1}{\sqrt[4]{\pi}}(e^{j\omega_0 t} - e^{-(\omega_0)^2/2})e^{-t^2/2}, \quad (13)$$

where ω_0 is the central frequency of the mother wavelet. The second term, $e^{-(\omega_0)^2/2}$, is the correction term used to correct the non-zero mean of the complete sine of the first term. It becomes insignificant when $\omega_0 > 0$. The complex Morlet wavelet is defined as (Rueda et al., 2011):

$$\phi(t) = \frac{1}{\sqrt[4]{\pi}} e^{j\omega_0 t} e^{-t^2/2}. \quad (14)$$

Consider a signal $x(t)$ sample with the interval Δt. The CWT at the time step $b = k\Delta t$ is given by (Sadowsky, 1994; Torrence and Compo, 1998):

$$T(a, kT_s) \approx \Delta t a^{-1/2} \sum_{n=0}^{N-1} x(n\Delta t)\phi^*[\frac{(n-k)\Delta t}{a}]. \quad (15)$$

4 System Description

In order to evaluate the proposed methods based on STFT and CWT for frequency estimation, three case studies have been implemented. The case studies include synthetic and simulated waveforms. The current signals were analysed in offline mode for both methods.

The simulated results were obtained in a LV microgrid system presented in Fig. 1. The distributed generation is composed of generation with synchronous machine, a photovoltaic (PV) system, and a three-phase linear load. The synchronous machine is connected to the point of common coupling (PCC) by a transmission line of 100 km. In the middle of the line is connected a linear load and a fault simulator. For fault simulation the switch K, initially open, is closed. The power main is connect by a three-phase transformer, composed by Y-connected of three 5 kVA, 380/220 V(rms). Table 1 summarizes the main specifications of the LV microgrid system depicted in Fig. 1 (Nunes et al., 2017; Rocha, 2015).

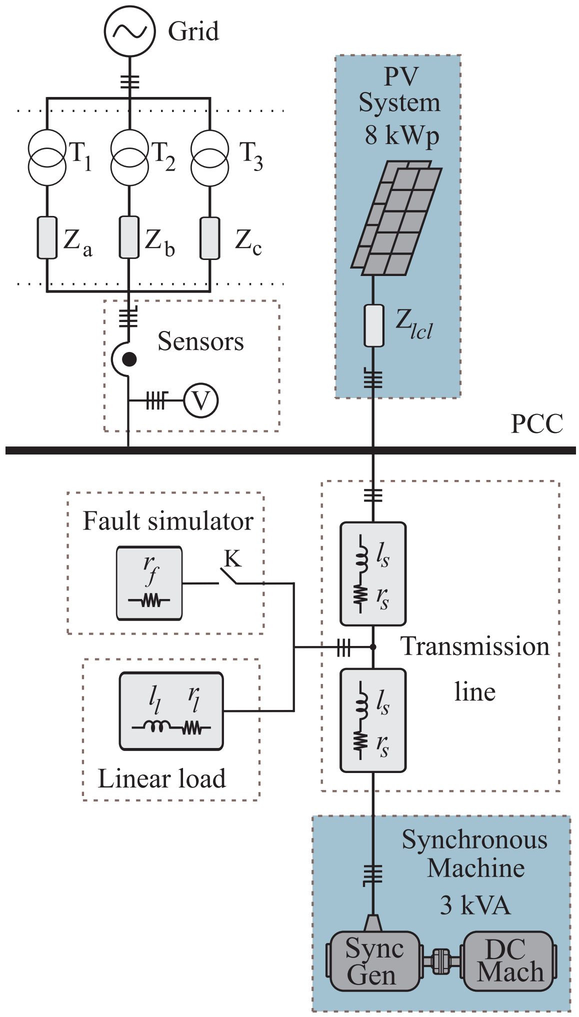

Figure 1: The low voltage microgrid system.

In a grid when any disturbance occurs both grid and microgrid are affects (Dehghanpour and Afsharnia, 2015), and there are frequency control difficulties. The currents of the microgrid system (Fig. 1) are analyses to check the frequency variations. In this work, the frequency variations happen in the microgrid when the DGs are connect with the power main and in the fault occurs.

5 Frequency Estimation of Synthetic Signals

Synthetic signals with known frequency variations were useful in this work in order to test the limits of the frequency estimation methods. The synthetic signals have unit magnitude. Then, the analyses are not influenced by others factors such as transients and magnitudes fluctuations. Consider a synthetic signal $i(t)$ with frequency variation from 60 to 59.5 Hz after 0.5 s ($\pm 1\%$ of the nominal system frequency). The synthetic signal is defined as:

Table 1: Systems Specifications

Parameter	Value
Primary voltage	380/220 V
Secondary voltage	220/127 V
Transformer power	15 kVA V
PV system power	8 kWp
Sync. machine power	3 kVA
Fault impedance	$r_f = 5\ \Omega$
Linear load	$r_l = 20\ \Omega$, $l_l = 60$ mH
Transmission line	$r_s = 0.1\ \Omega$, $l_s = 2$ mH
LCL filter	$Z_{lcl} = 0,49\angle 60,9^o\ \Omega$

$$i(t) = \begin{cases} \cos(2\pi 60t), & \text{if } t \leq 0.5 \text{ s} \\ \cos(2\pi 59.5t), & \text{if } t > 0.5 \text{ s} \end{cases} \quad (16)$$

Fig. 2 is shows the synthetic signals with a fundamental frequency of 60 Hz and a change in frequency to 59.5 Hz at time t= 0.5 s. Fig. 2(b) depicts the frequency estimation by the CWT and Fourier methods with the sampling frequency of f_s = 1920 Hz (multiple of 60 Hz), whereas Fig. 2(c) presents the frequency estimation using the sampling frequency of f_s = 2000 Hz.

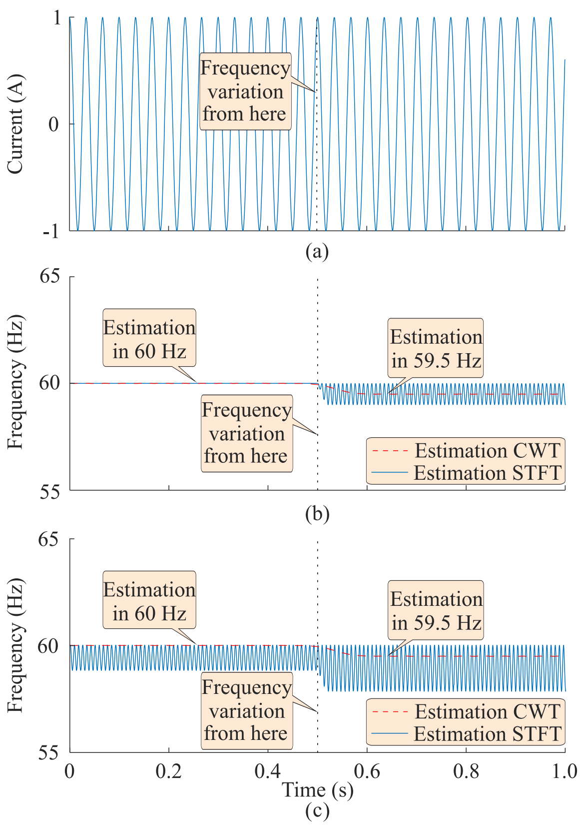

Figure 2: Synthetic waveforms: (a) current; (b) CWT and STFT with f_s = 1920 Hz; (c) CWT and STFT with f_s = 2000 Hz.

In Fig. 2(b), the frequency estimate using both methods presented an error of 0% before the frequency change. However, after the frequency change, only the STFT method presented significant errors because the sampling frequency is no longer integer multiple of the real frequency (f_s = 59.5 Hz). The STFT methods present problems in the frequency estimation when the sampling frequency or the signal frequency are not integer multiple of the fundamental frequency (Phadke and Thorp, 2008).

According to the Fig. 2(c), the frequency estimation using the CWT-based method does not present error when the sampling frequency is not multiple integer number of the fundamental frequency. Conversely, there is an error in the frequency estimation using the STFT-based method, which is related to the synchronization error of the window width employed that occur when the sampling frequency is not a multiple of 60 Hz. In addition, the error in the frequency estimation using the CWT-based method was 0%, presenting only a slight deviation during a frequency change around 0.5 s.

The CWT-based method correctly estimates the frequency values close to the fundamental frequency, regardless of the sampling frequency or signal frequency. Meanwhile, the frequency estimation based on the Fourier method is directly influenced by the sampling and signal frequency. In practical applications, the frequency in the power systems can not be constant in the stead-state. Then, the STFT-based methods have problems in practical applications because the signal frequency is not constant in 50 or 60 Hz.

6 Performance Assessment in Simulation

This section includes cases studies of frequency estimation of currents obtained in the microgrid system presented in Fig. 1 considering different operating conditions. The analyses are performed in off-line mode with sampling frequency of 1920 Hz.

6.1 First Case Study

In the first case study is the system composed by the power main and the linear load. At time t = 1.0 s the synchronous machine is connected in the PCC. Fig. 3 depicts the system current signal and the frequency estimation by both CWT and STFT methods. When transients occur in the system, frequency variations are expected. In this case study, when the synchronous machine is connected in the PCC a frequency variation occurs in the system. Both methods can estimate the fundamental frequency of the grid before connection and detect the frequency variation in instant of connection the synchronous machine. When the synchronous machine operates connected to the system, the frequency of the network varies

± 0.02 Hz in steady station, not being more constant in 60 Hz. After the frequency variation, an error appears in the frequency estimated by the STFT method (Fig. 3(c)) due the frequency of the grid varies around the fundamental frequency. This does not occur in the frequency estimation with CWT method (Fig. 3(b)) because the size of the CWT filter depends on the sampling frequency and not on the fundamental frequency.

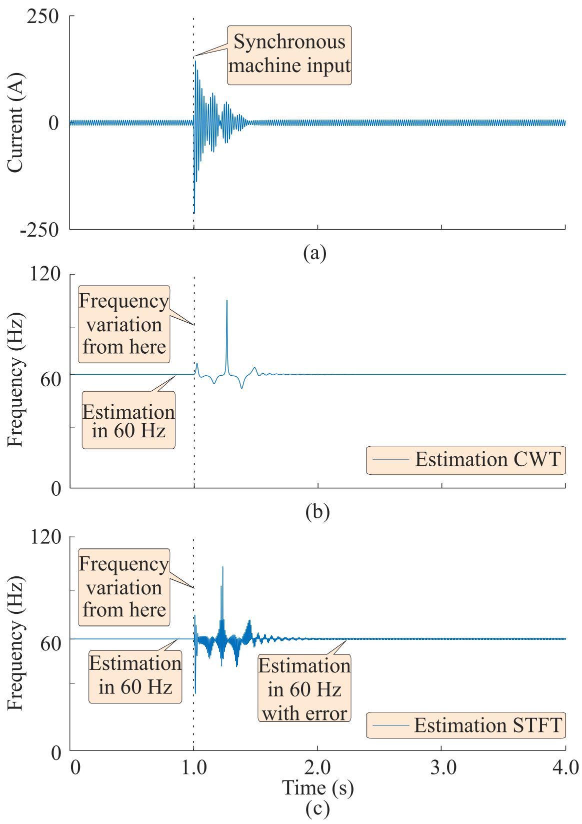

Figure 3: Simulated Signal with power main, the three-Phase linear load and synchronous machine: (a) current; (b) CWT; (c) STFT.

6.2 Second Case Study

In the second case study, at the instant 2.4 s, the PV system is connected to the PCC of the system of the first case study. Fig. 4 depicts the current signal of the system and the frequency estimation by the CWT and STFT methods. In the estimation of the frequency by the CWT (Fig. 4(b)) and STFT (Fig. 4(c)) methods the frequency variation is observed when the synchronous machine and the PV system are connected to the network, as expected. After the frequency variation, the frequency estimation by the STFT method oscillates around 60 Hz. When the PV system is connected the frequency system oscillate ± 0.03 Hz. Then, after the connection of the PV system the frequency estimation by STFT method has a greater error than the first case study. The CWT method is not affected by the oscillate frequency in the steady station.

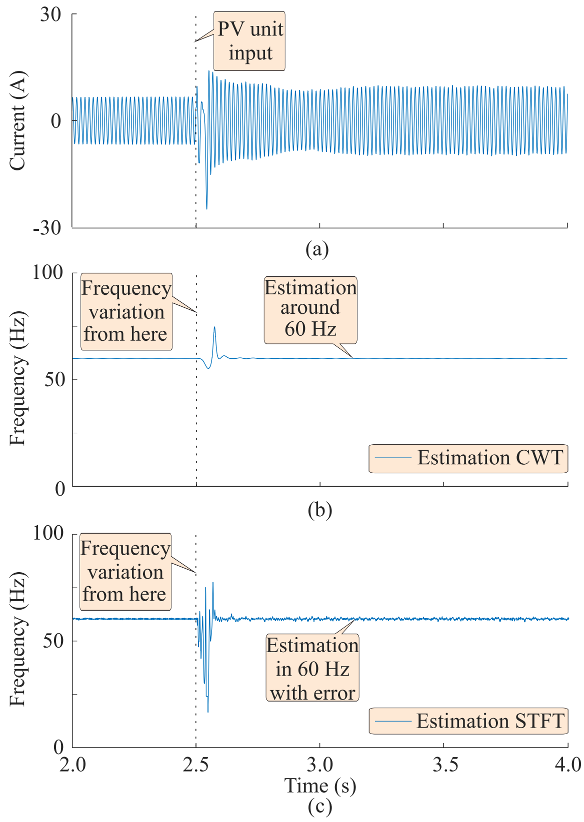

Figure 4: Simulated signal with power main, the three-phase linear load, synchronous machine and PVS: (a) current; (b) CWT; (c) STFT.

6.3 Third Case Study

The last case study includes an analyse of the microgrid system under the condition of fault. Fig. 5 depicts the system current and the frequency estimation by the CWT and STFT methods. A temporary three-phase fault is simulated with impedance 5 Ω. At 4.4 s the switch K, in the Fig. 1, is closed and after 0.8 s the switch K is open. In the current (Fig. 5(a)) is shown the connection of the synchronous machine, the PV system, and temporary three-phase fault. In all the occurrences, there is variation in the frequency when the system configuration changes. Both frequency estimation detecting all frequency variations at the same instant they occur. As in previous cases, the STFT method to frequency estimation presented an error in the estimation of the exact value of the frequency in the stead station after the occurrence of the events in the system, and the frequency estimation by the CWT method is not affected by the frequency oscillations in the stead station.

The methods have similar performance in the frequency estimation in the steady station when the sampling frequency is multiples of 60 Hz and the signal has constant frequency, equal to funda-

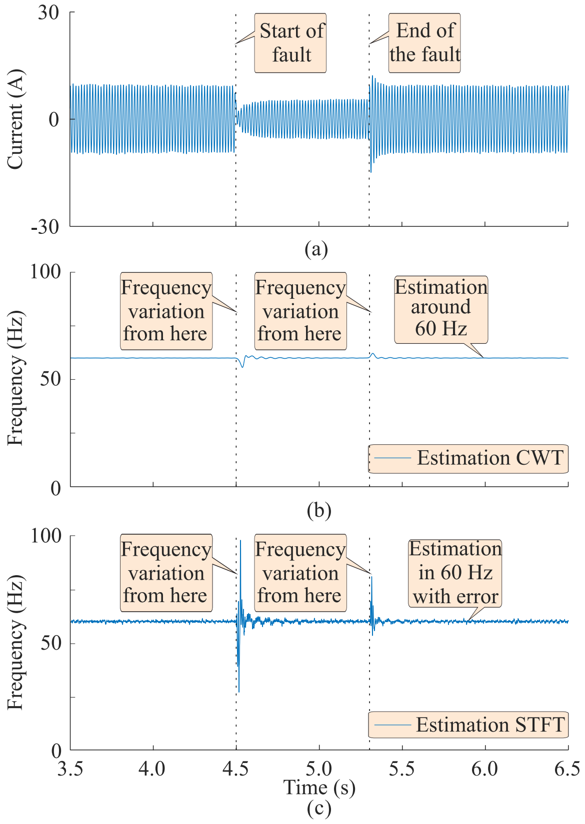

Figure 5: Microgrid with fault: (a) current; (b) CWT; (c) STFT.

mental frequency. When the sampling frequency used is not a multiplies of the fundamental frequency, the frequency estimated by the STFT method is not correct. None of the problems occur in frequency estimation using the CWT. The size of the CWT filter depends on the sampling frequency. Then, for high sampling frequency delays occur in the detection of transients. Depending on the chosen mother wavelet function, this delays can be larger or smaller. In online applications, CWT has high implementation complexity. In the future work, it will be investigated the impact of the choice of sampling frequency for the two techniques of frequency estimation and the changes in the frequency estimation of the CWT due to the variation of the mother wavelet.

7 Conclusion

In this work, a comparison between two methods of frequency estimation, a method based on CWT and a method based on STFT was performed. The CWT-based method can estimate the fundamental frequency of the signal (60 Hz) and frequency variations when a system change occurs, such as the synchronous machine connection, the PV system connection or a fault. The STFT-based frequency can only estimate the fundamental frequency of the signal when the sampling frequency is an integer multiple of the fundamental frequency. In addition, when the frequency of the system is different from 60 Hz, the estimated frequency will be an oscillation around the new frequency value. Therefore, the CWT-based method was more efficient for the analysed cases than the STFT-based method. However, other analyses should be done such as the impact of the choice of sampling frequency and the variation of the mother wavelet.

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