A wavelet-based hybrid islanding detection system applied for distributed generators interconnected to AC microgrids

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ABSTRACT

The modern distribution system widely uses renewable energy sources (RESs) as a distributed generation that introduces some problems like unintentional islanding, protection concerns, and reverse power flow. Islanding or fault occurrences must be detected and treated to ensure system stability. The literature presents several islanding detection methods classified as passive (PDM), active (ADM), or hybrid detection methods (HDM). HDMs present advantages of both PDM and ADM methods and overcome their inherent drawbacks. This paper proposes a modification on the CWT for accomplishing its real-time implementation (RT-CWT), and the use of its nonstationary signal analysis for implementing a wavelet-based hybrid islanding detection scheme (WB-HIDS). The evaluation of some power quality-related indices: power grid voltage, frequency deviation, grid impedance, and power angle enables the detection of islanding condition or fault occurrence. The simultaneous use of various indices mitigates the non-detection zone related to the PDM. Also, the use of a transient detection scheme for triggering the signal injection implementation minimizes undesired disturbances introduced by ADM schemes. Experimental results obtained from an ac microgrid laboratory setup validate the proposed solution and demonstrate its effectiveness.

1. Introduction

Most of the conventional distribution systems have radial configuration, and the power flow from the power mains to the downstream loads is unidirectional [1]. Conversely, modern distributed systems that employ distributed generation (DG) implemented via renewable energy sources (RESs) have bidirectional power flow. In this case, multiple sources impact the adjustment of the system protection, resulting in a new paradigm [2]. The introduction of RES into the distribution network can modify the system parameters, such as voltage and frequency because these sources are inherently intermittent. Moreover, RES interconnects to the network via a power converter operating as an active front-end, which introduces harmonic distortion.

In the RES high penetration level, the DGs islanded operation mode can maintain system continuity and reliability. However, a secure transition to the islanded operation requires fast, precise, and cost-effective islanding detection methods (IDMs) [3]. In the last few years, several types of IDMs have been proposed for DG units. According to the IEEE Std. 1547 [4], the islanding condition should be detected within 2 s after its occurrence. Generally, the IDMs can be classified into passive detection methods (PDMs), active detection methods (ADMs), and hybrid detection methods (HDMs) [3].

The PDMs employ measurements obtained from the point of common coupling (PCC) voltages, currents, and frequency. Several passive methods such as over/under voltage and frequency deviation [1,5–8], rate of change of frequency (ROCOF), over system power [9], harmonic monitoring [1,9], phase jump detection [1,9,10], and voltage vector shift [9,11,12] have been developed to detect the islanding operational condition. The most commonly PDMs are based on phase jump and harmonic detection. The voltage bias from the nominal value determines the phase jump occurrence, whereas the PCC total harmonic distortion (THD) greater than 5% addresses a possible nominal violation. In the presence of a stiff utility voltage, small grid impedance guarantees the THD required limits. These methods have a low-cost implementation because they use standard measurement devices, not affecting the system power quality [9,13]. However, they present a large non-detection zone (NDZ) during transient periods that lead to PCC parameter variations. This side effect can result in false detections for balanced load and power conditions or during significant load/generation changes [9]. Furthermore, PDM may fail in islanding...
The ADM approaches employ the perturb and observe concept by using a noncharacteristic signal injection into PCC. Under the stiff grid, the PCC nominal parameters are dominant. However, during an islanding occurrence, they vary significantly and can be detected by analyzing the system response on the frequency domain. Several methods such as impedance measurement [2,14,15], active frequency drift [9,16], frequency jump [9], sandia frequency shift [1,14,17,18], sliding mode frequency shift [2,14,17,19], phase distortion method [9,20,21], harmonic injection method [2,9,13], sandia voltage shift [9,17], power variation monitoring [9,14], and reactive power export error detection [9,15,22] have been developed for detecting islanding conditions. In these methods, a non-characteristic signal injection perturbs the system parameters, and the observation of their possible deviation indicates a possible islanding detection. In general, ADMs have reduced the NDZ area with small values or even zero compared to the PDMs [9,20]. However, ADMs generate power quality issues, suffer from interference in the presence of multiple DGs, and could be ineffective for islanding detection of synchronous generators DGs [9,20].

The HDMs integrate the PDMs and ADMs, and in some cases, control strategies to assure a smooth transition between connected and islanding modes. This combination increases the detection accuracy [23–25]. The development of HDMs overcome the drawbacks of both PDMs and ADMs and improves the islanding detection capability. Moreover, the employed signal processing can extract the unseen system parameter information [9,26,27]. The extraction of this hidden information can reveal the occurrence of parameter deviations. Furthermore, the integration of both methods as an HDM reduces the NDZ.

The HDMs have been implemented with different techniques and employed for islanding detection in different networks. The optimized sandia frequency shift associated with the passive method ROCOP to implement a hybrid detection scheme for inverter-based DGs [23]. A fuzzy-neural network implemented a hybrid islanding detection applied for a microgrid with multiple connection points [24]. The reactive power control (RPC)-based technique has also been employed for islanding detection by monitoring the PCC voltage vector angle deviation [25]. The use of positive feedback and voltage unbalance and total harmonic distortion implemented a hybrid detection scheme in [28]. Also, the average rate of voltage change associated with the real power shift consisted of the detection technique employed in [29]. Hybrid methods have some limitations produced by active methods that depend on the primary source of DG, and the type of interconnected loads [29]. The duration of the signal injection or control actions provided by those systems could be adjusted to overcome these drawbacks, as implemented in [28–30]. Moreover, the islanded thresholds could also be adapted for providing accurate detections. Statistics approaches have also been proposed for adjusting the detection thresholds as the probability of islanding (PoI) introduced in [24]. The combination of islanding detection methods (i.e., passive, active, and communication-based techniques) based on the wavelet transform associated Neural-fuzzy networks determine the proposed PoI [24].

Advanced signal analysis, like a short-time discrete Fourier transform (STFT) [31] and discrete wavelet transform (DWT) [6], can mitigate the NDZ of the PDMs. Despite the STFT employs the time—frequency window to localize the transients, since it uses a fixed window size, the STFT cannot operate with multiresolution [32]. Therefore, if the frequency increases, further cycles appear in the fixed window reducing its effectiveness in the localization of individual frequency components. Unlike STFT, the DWT uses different windows for signal analysis, which corroborates to the solution of this drawback. For that reason, several islanding detection approaches based on the DWT have been introduced [33–36]. The DWT is commonly used for detecting disturbances in power systems due to its sensibility to signal irregularities while it is insensitive to standard signal conditions.

The PDMs based on DWT can be divided into non-energy- and energy-based observations [6,11,35,37]. Regarding the non-energy-based analysis, the PDM implemented by using the comparison of an arbitrary threshold to voltage and frequency DWT coefficients was proposed in [35]. Similarly, the use of analysis of the output power in the wavelet domain was introduced in [37]. The direct use of arbitrary thresholds could result in misdetection, lead to nuisance tripping, which addresses the use of wavelet coefficient energy-based analysis. In this direction, a PDM that employs the analysis of the negative sequence voltage coefficient energy at the first decomposition level was implemented by [38]. Also, voltage and current wavelet coefficient energies were employed for implementing PDMs in [6,11]. However, in three-phase systems, the use of phase voltages and currents increases the computational burden.

The main drawback of the DWT is related to the batch processing step and its inability for detection under noisy conditions. These limitations can be overwhelmed by using the discrete S-transform (DST), which can detect various islanding and power quality disturbances [38–42]. A comparison study about the use of DWT and DST in an islanding detection scheme was shown in [38]. In this method, the extraction of suitable statistical features based on standard deviation and energy, associated with appropriate thresholds addresses to the islanding detection. However, in the presence of some non-stationary signals accompanied by transients, the DST detection effectiveness could be reduced [43]. A new wavelet approach, namely WGM1.0, that uses Procrustes analysis, and a support vector machine (SVM) were proposed in [44] for reducing the computational burden and overcome these undesired errors. In this PDM, the index obtained from DST is assessed by evaluating the classification models developed by SVM and ensemble tree classifier by using the model accuracy and harmonic metrics.

The use of linear hyperbolic S-transform, associated with time to time transform and mathematical morphology method mitigates limitations related to the DST [45]. This methodology provides the detection of the islanding occurrence, even under the presence of noise conditions. In the DWT, at any level of decomposition, only the scaling coefficients are decomposed, i.e., the wavelet coefficients never are split up. In the discrete wavelet packet transform (DWPT), both scaling and wavelet coefficients are decomposed. As the main advantage, the DWPT provides uniform output frequency bands, allowing the DWPT provides frequency information more accurately than conventional DWT [32]. Moreover, its association with the backpropagation neural network provides the islanding detection of DGs grid-connected power converter, mitigating the NDZ and avoiding threshold selection. However, the continuous wavelet transform (CWT) can generate the required data for realizing effective islanding detection. Nevertheless, conventional CWT is a highly redundant transformation, commonly used in off-line applications [46]. Indeed, the computational burden associated with its implementation makes it unsuitable for real-time applications.

This paper proposes a modification on the CWT for accomplishing its real-time implementation (RT-CWT), and the use of its non-stationary signal analysis advantages for implementing a wavelet-based hybrid islanding detection scheme (WB-HIDS). The use of the RT-CWT improves the advantage of the non-stationary signal analysis for generating power quality-related indices. Also, the proposed WB-HIDS employs a transient detection scheme, based on energy coefficients, that permits to mitigate the power quality issues related to the signal injection (i.e., drawback inherent to ADM approaches) by limiting the duration of its implementation only when a transient has occurred. The evaluation of the islanding conditions is provided through the analysis of a data set composed of power quality indices, such as voltage amplitude, event duration time, unbalanced degree, system frequency, grid impedance as well as power angle. The use of various indices allows for the correct distinction between islanding condition or fault occurrences, reducing the errors produced by the NDZ that is inherent to PDM schemes. Experimental tests obtained from an ac microgrid laboratory setup operating under several scenarios validated the
The proposed solution and demonstrated its effectiveness.

2. System description

Fig. 1 depicts the ac microgrid setup laboratory used for validating the proposed WB-HIDS. It comprises three distribution generators: a three-phase PV system, a wind-power emulator (WPE), and hydro-power emulator (HPE). A permanent magnet synchronous generator (PMSG) driven by a servo-drive system implements the WPE, while a salient-pole synchronous machine emulates the HPE. Grid-feeding power converters (LCL-VSC) interconnects the PV system and WPE to the PCC. A bidirectional buck-boost dc/dc power converter interlink an energy storage system of 60 V, composed of a series association of five batteries of 12 V, 220 Ah, as energy storage system (ESS). A concentrated transmission line model \( Z_{cl} \) provides the interconnection of the HPE to the power grid. Controlled switches \( S_1 - S_4 \) implement the operational scenarios employed in the WB-HIDS evaluation tests. Switches \( S_1 - S_3 \) together with resistive branches \( r_F = 5 \Omega \) implement the short-circuit fault emulator, and \( S_4 \) simulates an open-circuit fault occurrence. The emulation of the islanding condition of the PV system employs switches \( S_1 - S_5 \) for inserting external impedances \( Z_{ext} \) series connected to the converter LCL filter. Finally, controlled switch \( S_5 \) implements the HPE islanding operation.

A three-phase 15 kVA-380/220 V substation implements the primary power grid of the microgrid laboratory setup. The PV system employs the most commonly multiloop control strategy in which the internal control loop regulates the DG output phase currents, and the outer control loop sets the dc-link voltage. The bandwidths of the current controllers were adjusted for allowing the required interharmonic injection. A fast prototyping platform dSPACE 1103 and a DSP TMS320F28335 execute the microgrid control algorithms. Table 1 presents the main parameters of the experimental microgrid of Fig. 1.

3. Basis of continuous wavelet transform

The wavelet transform highlights irregularities of the signal through the amplitude of their coefficients [47]. The wavelet function \( \psi_{a,b} \) has dilation \( a \) proportional to translation \( b \) with its time support centered at dilation [47]. Therefore, the CWT can decompose a signal into the time-frequency representation and guarantee the temporal and spectral resolutions in the frequency range [48,49]. The mother wavelet \( \psi \) is a window function that builds the wavelet transform and can be written compactly from normalisation mother wavelets as follows [50]:

\[
\psi_{a,b}(t) = \frac{1}{\sqrt{a}} \psi \left( \frac{t-b}{a} \right),
\]

where \((t - b)/a\) is associated to the dilation and translation in time of the wavelet function, and the term \(1/\sqrt{a} \) is the normalization factor, conventionally used for purposes energy conservation, which guarantee the same energy of the wavelets at every scale [50].

The CWT of a continuous-time domain signal \( x(t) \) to different \( a \) and \( b \) is mathematically defined as [47]:

\[
X(a,b) = \int_{-\infty}^{\infty} x(t) \psi_{a,b}^*(t) dt,
\]

where \( \psi_{a,b}^*(t) \) is the complex conjugate of \( \psi_{a,b}(t) \).

The Morlet mother wavelet is well-suited for non-stationary signals analysis providing the detection of their irregularity characteristics through its localized filters in the time–frequency domain [49,51]. For that reason, it has been commonly used in different applications to supervise power system disturbances [34,51–54], identify oscillation modes [55], damp ratios and natural frequencies [56], estimate frequency and phase [57], diagnose faults [52,58,59], and estimate grid impedance [46]. Therefore, the choice of the Morlet wavelet to implement the RT-CWT assures the required performance on the estimation of signal amplitudes and their phase angles.

The complex Morlet mother wavelet for \( \omega_0 > 0 \) is given by [50]:

\[
\psi(t) = \frac{1}{\sqrt{\pi}} e^{i \omega_0 t} e^{-\frac{t^2}{2}},
\]

where \( \omega_0 = 2\pi f_c \) in which \( f_c \) is the central frequency of the mother wavelet.

4. The Proposed RT-CWT

This paper accomplishes some modifications in the CWT and Morlet wavelet to become suitable for real-time applications. Therefore, considering \( x(k) \) as a discrete signal and \( \psi_{a,b}^*(k) \) as a discrete wavelet with a sampling rate given by \( k/f_s \), in which \( k = 0, 1, \ldots, \) and sampling frequency \( f_s \), the CWT of the discrete signal can be approximated to:
\[ \hat{X}_k(k) = \frac{1}{f_s} \sum_{n=-\infty}^{\infty} x(n) \psi_{\nu}^*(n-k+\eta-1), k \geq \eta - 1. \]  

(4)

where \( \eta \) is the wavelet filter length, \( \hat{X}_k(k) \) is the complex vector estimated by the CWT in the sampling \( k \). In real-time analysis, \( k \) is always the current sampling (i.e., there are no samples above the index \( k \)).

The complex conjugate Morlet wavelet in a discrete-time domain is given by:

\[
\psi_{\nu}^*(n-k+\eta-1) = \frac{1}{\sqrt{\nu}} e^{-\frac{(n-k+\eta-1)^2}{2{\sigma_n^2}}} 
\cos \left( \frac{2\pi f_0 (n-k+\eta-1)}{\nu} \right) - j \sin \left( \frac{2\pi f_0 (n-k+\eta-1)}{\nu} \right). 
\]

(5)

The real and imaginary CWT coefficients are obtained from (4) and (5), as follow:

\[
X_{\nu,\text{real}}(k) = \frac{1}{f_s} \sum_{n=-\nu+\eta}^{\nu-1} x(n) e^{-\frac{(n-k+\eta-1)^2}{2{\sigma_n^2}}} 
\cos \left( \frac{2\pi f_0 (n-k+\eta-1)}{\nu} \right), k \geq \eta - 1. 
\]

(6)

\[
X_{\nu,\text{imag}}(k) = \frac{1}{f_s} \sum_{n=-\nu+\eta}^{\nu-1} x(n) e^{-\frac{(n-k+\eta-1)^2}{2{\sigma_n^2}}} 
\sin \left( \frac{2\pi f_0 (n-k+\eta-1)}{\nu} \right), k \geq \eta - 1. 
\]

(7)

From the complex vector of the signal computed through (6) and (7), the instantaneous magnitude and phase is given by:

\[
X_k(k) = \sqrt{X_{\nu,\text{imag}}(k)^2 + X_{\nu,\text{real}}(k)^2}, 
\]

(8)

\[
\theta_{\nu,k}(k) = \tan^{-1} \left( \frac{X_{\nu,\text{imag}}(k)}{X_{\nu,\text{real}}(k)} \right). 
\]

(9)

5. Proposed indices for islanding detection

From (8) and (9) the magnitude and phase of the power grid voltage estimated by CWT are given by

\[
V_k(k) = \sqrt{\left(X_{\nu,\text{imag}}(k)\right)^2 + \left(X_{\nu,\text{real}}(k)\right)^2}, 
\]

(10)

\[
\theta_{k,V}(k) = \tan^{-1} \left( \frac{V_{\nu,\text{imag}}(k)}{V_{\nu,\text{real}}(k)} \right). 
\]

(11)

Similar procedure can be applied to the power grid current vector, which results in

\[
I_k(k) = \sqrt{\left(I_{\nu,\text{imag}}(k)\right)^2 + \left(I_{\nu,\text{real}}(k)\right)^2}, 
\]

(12)

\[
\theta_{k,I}(k) = \tan^{-1} \left( \frac{I_{\nu,\text{imag}}(k)}{I_{\nu,\text{real}}(k)} \right). 
\]

(13)

In the proposed method, the estimations of the power grid voltage and current vectors are analyzed for detecting possible voltage deviations and used for calculating the power grid unbalanced degree, the energy of the coefficients, frequency and impedance estimation, and power angle.

5.1. Estimation of the power grid unbalanced degree

The presence of negative sequence terms in a three-phase power grid can indicate possible fault occurrences. This asymmetry is verified when the power grid phase voltages have different amplitudes and/or asymmetric phase displacements. The voltage estimation defined in (10) can be used in each system phase to obtain the zero \( (V_{\nu,\text{real}}) \), positive \( (V_{\nu,\text{real}}^+ \) and negative \( (V_{\nu,\text{real}}^-) \) sequences, by using:

\[
\begin{bmatrix}
V_{\nu,\text{real}}^0(k) \\
V_{\nu,\text{real}}^+(k) \\
V_{\nu,\text{real}}^-(k)
\end{bmatrix} = \begin{bmatrix}
1 & 1 & 1 \\
1 & \alpha & \alpha^2 \\
3 & 1 & \alpha^2
\end{bmatrix} \begin{bmatrix}
V_{\nu,k}(k) \\
V_{\nu,b}(k) \\
V_{\nu,c}(k)
\end{bmatrix} 
\]

(14)

where \( V_{\nu,k}, V_{\nu,b}, \) and \( V_{\nu,c} \) are the phase voltage magnitude, and \( \alpha = e^{i\frac{2\pi}{3}} \) is the rotation operator.

The most general form to obtain the power grid unbalanced degree is to compute the ratio between the negative and positive phase sequence components [60], which can be expressed by

\[
\%V_k(k) = \frac{V_{\nu,\text{real}}^-(k)}{V_{\nu,\text{real}}^+(k)} \times 100. 
\]

(15)

5.2. Grid frequency estimation

The CWT-based filters have complex coefficients that permit to extract phase information via signal analysis. Based on this phase information, it is possible to estimate the frequency. The power grid frequency estimation corresponds to the time-derivative of the voltage displacement angle. From (11), it is possible to compute the displacement angles at two sampling instants (i.e., \( \theta_{k,V}(k) \) and \( \theta_{k,V}(k-1) \)), which divided by the sampling rate (i.e., \( 1/f_s \)) results in the power grid frequency estimation given by:

\[
f_k(k) = \frac{\theta_{k,V}(k) - \theta_{k,V}(k-1)}{2\pi f_s}. 
\]

(16)

The frequency deviation denotes the power energy unbalanced issue that could be used to identify possible islanding conditions or fault occurrences.

5.3. Energy of the coefficients as the WB-HIDS trigger

Active impedance estimation methods employ a signal injection approach that could result in undesired power quality issues. The mitigation of these effects can be achieved if the signal injection is provided only during the power system changing due to system disturbances like faults or islanding occurrences. The analysis of the wavelet coefficient energy of voltages and currents obtained through RT-CWT determines a power system modification. Therefore, the increase of these energies upper than standard limits can be used to trigger the WB-HIDS for providing the grid impedance estimation.

According to Parseval’s theorem, the energy of a function can be given by the integral of its squared magnitude [50]. Besides, the Morlet wavelet transform is a complex function, in which the magnitude also determines its energy spectrum. Therefore, the real-time wavelet coefficient energy of voltage \( (E_{k,V}) \) and current \( (E_{k,I}) \) can be expressed as:

\[
E_{k,V}(k) = \sum_{n=-\nu+\eta}^{\nu-1} V_e(n)^2, 
\]

(17)

\[
E_{k,I}(k) = \sum_{n=-\nu+\eta}^{\nu-1} I_e(n)^2. 
\]

(18)

The proposed method computes the wavelet coefficient energy of both voltage and current by using (17) and (18) in each sampling time and compares with their precedent values for detecting power system modifications. Therefore, the voltage \( (|D_{k,V}|) \) and current \( (|D_{k,I}|) \) deviations can be expressed as follows:

\[
|D_{k,V}(k)| = |E_{k,V}(k) - E_{k,V}(k-1)|, 
\]

(19)

\[
|D_{k,I}(k)| = |E_{k,I}(k) - E_{k,I}(k-1)|. 
\]

(20)

The dynamic average of the deviations \( |D_{k,V}(k)| \) and \( |D_{k,I}(k)| \) are continuously computed, in which threshold limits delimit the allowed...
system operation. Based on this setup, the system modification occurs if at least one of these energy deviations extrapolates the allowed upper limits. The adoption of a hysteresis band avoids false detections. In this sense, the use of an energy threshold of three times the wavelet coefficients energy average (calculated during one cycle) has been proposed in [61] for detecting power system transients. Experimental tests demonstrated that the adoption of this criterion is also suitable for the proposed WB-HIDS. According to this methodology, the maximum allowed voltage or current deviations can be given by:

\[
\text{Trigger}_k = \begin{cases} 
3|\Delta I_{k,\text{intra}}(k)| \\
3|\Delta D_{k,\text{intra}}(k)|
\end{cases}
\]  \tag{21}

Considering that (21) is satisfied, the proposed method triggers the WB-HIDS signal injection procedure for a while for providing the updating of the grid impedance estimation. The duration of the trigger pulse should be enough to be recognized by the grid impedance module for providing the signal injection. The trigger signal in the experiments has a duration equivalent to the duration of the transient.

### 5.4. Grid impedance estimation approach

Active steady-state methods for the grid impedance estimation depend on the magnitude, frequency, and repetition rate of the interharmonic injection. Details about the injection current, such as what amplitude and frequency to employ, are not a consensus among the researchers, i.e., some methods inject high-frequency signals, whereas others inject low-frequency signals like interharmonic. These signal injection procedures must take into account the compromise between the signal-to-noise ratio (SNR) and the total harmonic distortion (THD).

In general, the interharmonic injection must be as small as possible for not disturbing the power grid. However, the choice of its magnitude must be suitable for accomplishing a required estimation. The impedance estimation approach of proposed WB-HIDS follows the methodology proposed in [62], which suggests an interharmonic of 1.5 times the fundamental frequency with the magnitude of 3 A. Experimental tests shown that this condition is also suitable for experimental setup employed in this work.

The duration of the trigger pulse should be enough to be recognized by the grid impedance module for providing the signal injection. The trigger signal length of time, in the experiments, is equivalent to the duration of the transient occurrence. In this work, the interharmonic injection takes eight cycles of the fundamental frequency for an accurate grid impedance estimation. The bandwidth of the Morlet wavelet filter is proportional to the sampling frequency, which is 1920 Hz. Therefore, \( \eta \) is about six cycles. The impedance is estimated as the average instantaneous impedance values during the last two periods of the fundamental frequency before removing the interharmonic. Different setups related to the interharmonic amplitude, frequency, and duration can be employed.

The dynamic phasors of the DG output voltage (\( \vec{V}_{\text{g,intra}} \)) and current (\( \vec{I}_{\text{g,intra}} \)), on the signal injection frequency, are given by

\[
\vec{V}_{\text{g,intra}}(k) = V_{\text{g,intra}}(k) e^{j \phi_{\text{g,vol}}(k)},
\]
\[
\vec{I}_{\text{g,intra}}(k) = I_{\text{g,intra}}(k) e^{j \phi_{\text{g,intra}}(k)},
\]  \tag{22, 23}

where the grid impedance on the interharmonic signal frequency can be defined as follows:

\[
\vec{Z}_{\text{g,intra}}(k) = \frac{\vec{V}_{\text{g,intra}}(k)}{\vec{I}_{\text{g,intra}}(k)}.
\]  \tag{24}

The estimated value of the grid resistance (\( R_{g,k} \)) does not depend on the interharmonic frequency and corresponds to the real part of (24), which address to:

\[
R_{g,k} = \frac{V_{\text{g,intra}}(k)}{I_{\text{g,intra}}(k)} \cos(\phi_{\text{g,vol}}(k) - \phi_{\text{g,intra}}(k)).
\]  \tag{25}

The imaginary part of \( \vec{Z}_{\text{g,intra}}(k) \) refers to the estimated reactance on the interharmonic frequency (\( X_{\text{g,intra}}(k) \)):

\[
X_{\text{g,intra}}(k) = \frac{V_{\text{g,intra}}(k)}{I_{\text{g,intra}}(k)} \sin(\phi_{\text{g,vol}}(k) - \phi_{\text{g,intra}}(k)).
\]  \tag{26}

The following simple mathematical procedure determines the grid reactance (\( X_{g}(k) \)) on the power grid fundamental frequency:

\[
X_{g}(k) = \frac{\omega_0 X_{\text{g,intra}}(k)}{\omega_{\text{inter}}},
\]  \tag{27}

where \( \omega_0 \) is the fundamental frequency of the system and \( \omega_{\text{inter}} \) is the interharmonic frequency. Consequently, the grid impedance on the fundamental frequency (50 or 60 Hz) is estimated by

\[
Z_{g}(k) = \sqrt{(R_{g,k}(k))^2 + (X_{g}(k))^2}.
\]  \tag{28}

### 5.5. Power angle estimation

The knowledge of the microgrid power angle can address to system modifications like islanding conditions of fault occurrences. It is possible to estimate the power angle at the DG units or the power mains. The method employed in this work estimates the system power angle through the active and reactive power calculated at the PV system, according to the following expressions:

\[
P_{g}(k) = \frac{E V_{g}(k)}{Z_{g}(k)} \cos(\delta_{g,Z}(k) - \phi_{g}) = \frac{V_{g}(k)^2}{Z_{g}(k)} \cos(\delta_{g,Z}(k)),
\]  \tag{29}

\[
Q_{g}(k) = \frac{E V_{g}(k)}{Z_{g}(k)} \sin(\delta_{g,Z}(k) - \phi_{g}) = \frac{V_{g}(k)^2}{Z_{g}(k)} \sin(\delta_{g,Z}(k)),
\]  \tag{30}

where \( E \) is the amplitude of the inverter output voltage, \( \phi_{g} \) is the power angle, and \( \delta_{g,Z} \) is the phase angle of the output impedance. Therefore, the estimation of the DG power angle can be obtained by using (29) and (30) as follows:

\[
\phi_{g}(k) = \arcsin\left(\frac{Z_{g}(k)[P_{g}(k) + Q_{g}(k) + U_{g}(k)]}{2\sin(\delta_{g,Z}(k))E V_{g}(k)}\right),
\]  \tag{31}

where \( U_{g}(k) \) is given by:

\[
U_{g}(k) = \frac{V_{g}(k)^2}{Z_{g}(k)}[\sin(\delta_{g,Z}(k)) + \cos(\delta_{g,Z}(k))].
\]  \tag{32}

### 6. The proposed wavelet-based hybrid islanding detection system

The proposed WB-HIDS generates a knowledge-based data system composed of the following power quality indices: PCC voltage amplitude, event duration, unbalanced degree, frequency deviation, grid impedance estimation, and DG power angle. The analysis of these indices under predefined thresholds constraints imposed by standards or grid codes determines possible islanding or fault conditions of the power grid. Most of the standards delimit some of these indices like the IEEE Std. 1547 [4] for voltage, frequency, and duration time; PREN 50330–1 [63] for acceptable grid impedance; or EN50160 [64], for unbalance limits. Some standards are more restricted, and for that reason, this paper adopted the most usual rule presented in Table 2.

The standard IEEE Std. 1547 presents the requirements and principles for the connection of distributed generation with the electric power system. According to this, under the occurrence of unintentional islanding condition, the distributed generation shall detect the event and disconnects the system in 0.16 or 2 s conforming to the voltage, frequency, and unbalance degree level. Furthermore, mutual agreement
between the operators of distributed generation and the power system could extend the to 5 s [4]. This work adopted the most general case in which the disconnection should take effect in 2 s. According to the standards summarized in Table 2, the prevailing characteristics of an islanding condition are an unbalanced degree greater than 2%, impedance variation higher than 0.5 Ω, voltage regulation higher than 5%, and frequency deviations superior to 0.5 Hz. They should remain last longer than 2 s to be considered an islanding occurrence. Events with these deviations with a window time inferior are considered faults, usually isolated by the power grid protection.

7. Performance assessment

The proposed WB-HIDS detection method employs the ac microgrid setup laboratory presented in Fig. 2 (i.e., related to the block diagram of Fig. 1) to evaluate its performance. Its structure was designed to support different operational conditions. For that reason, the converter power switches and interconnection switches are oversized. Those interconnection switches (contacts), commanded remotely through a control algorithm implemented in the dSPACE platform, provide the emulation of the different operational scenarios. The evaluation tests are composed of the following operational scenarios: (i) three-phase fault emulation; (ii) two-phase fault emulation; (iii) open-circuit fault emulation; (iv) PV system islanding emulation, and (v) HPE disconnection. The controlled switches $S_1 - S_3$ in Fig. 1 (i.e., the contacts in Fig. 2) provide the required system reconfiguration for implementing the operational scenarios. The proposed WB-HIDS detection method used a sampling frequency of $f_s = 1920$ Hz, which corresponds to 32 samplings per cycle of the fundamental ($f = 60$ Hz). The experimental results presented for each operational scenario are composed of a set of six graphs that depicts the following: voltage amplitude, trigger signal, unbalanced degree, grid frequency, grid impedance, and PCC power angle. The PCC voltage and current measurements, as well as the WB-HIDS, are implemented at the PV control system.

7.1. Scenario I - three-phase fault emulation

In this test, the controlled switches $S_1 - S_3$ interconnect a three-phase resistive load of $r_f = 5$ Ω at the PCC, increasing its phase currents in five times the steady-state values to emulate a three-phase fault condition. Fig. 3(a)-(f) depicts the experimental results obtained from this operational scenario for the PCC phase A. The WB-HIDS realizes the PCC voltage and current measurements and estimates the power quality indices. At the beginning of the experiment, the steady-state values of the power quality indices are voltage amplitude of $V_{p_u} = 135$ V, unbalanced degree of $\Delta_{un} = 0.6\%$, frequency of $f = 60.03$ Hz, grid impedance of $Z = 0.515$ Ω, and power angle $\phi = 0.027$ rad.

At $t = 0.5$ s, the controlled switches interconnect the three-phase load and remain in that condition for $t = 0.5$ s. The fault emulation produces an undervoltage of $V = 9$ V, as shown in Fig. 3(a). This voltage variation provokes an extrapolation of the upper limit of the energy coefficients determined by (21), which triggers the WB-HIDS (as depicted in Fig. 3(b)) for providing the other power quality indices. During the fault occurrence, the unbalanced degree of the PCC increases to $\Delta_{un} = 0.76\%$, as presented in Fig. 3(c). The PCC frequency suffers a deviation of $\Delta_f = 0.11$ Hz, according to Fig. 3(d). The grid impedance reduces to $Z = 0.4969$ Ω due to the interconnection of the

![Fig. 2. Experimental platform of low voltage microgrid system.](image)

![Fig. 3. Experimental results of three-phase fault emulation at the PCC: (a) PCC phase A voltage amplitude; (b) WB-HIDS trigger signal; (c) system unbalanced degree; (d) PCC frequency estimation; (e) grid impedance estimation; (f) PCC power angle.](image)
three-phase load, as depicted in Fig. 3(e), and the power angle decreases to \( \phi \approx -0.0074 \) rad.

At \( t = 1.0 \) s, the controlled switches \( S_1 - S_3 \) disconnect the three-phase load, clearing the fault occurrence, and the power quality indices returned almost to the same values of the beginning of the experiment. These experimental results demonstrated that proposed WB-HIDS could estimate deviations in the power quality indices that can be used to characterize the three-phase fault occurrence.

7.2. Scenario II - two-phase fault emulation

The main objective of this experiment is to evaluate the performance of the proposed WB-HIDS under inherently unbalanced conditions. The controlled switches \( S_1 - S_3 \) interconnect a two resistive single-phase \( (r_t = 5 \, \Omega) \), resistive loads to the PCC to emulate the two-phase fault occurrence. This interconnection causes an increase of five times the amplitudes phase currents \( A \) and \( B \) in PCC. Fig. 4(a)-(f) depicts the experimental results obtained from this operational scenario for the PCC phase \( A \) with the analogous procedure of the last experiment. At the beginning of the experiment, the steady-state values of the power quality indices are the same as the test present before.

The interconnection of a two-phase load occurs at \( t \approx 0.68 \) s and the remains linked to the PCC for \( \Delta t \approx 0.76 \) s. The fault emulation provokes undervoltages in the PCC phases \( A \) and \( B \) of \( \Delta V_{A,B} = 8.5 \, \text{V} \) and \( \Delta V_{B,A} = 5.7 \, \text{V} \), accordingly to Fig. 4(a). These voltage deviations extrapolate the upper limits of the wavelet coefficient energy delimited in (21), triggering the WB-HIDS to estimate the power quality indices, as shown in Fig. 4(b). The PCC unbalanced degree raises to \( \Delta_{\omega} = 2.63\% \), as presented in Fig. 4(c). The fault occurrence slightly modifies the PCC estimated frequencies to \( f_{A,B} = 60.16 \, \text{Hz} \) and \( f_{B,A} = 60.31 \, \text{Hz} \), as depicted in Fig. 4(d). In this test, the estimated impedances of phases \( A \) and \( B \) are plotted individually to highlight the effectiveness of the proposed method. At the beginning of the test, the impedance estimations were \( Z_{A} \approx 0.5724 \, \Omega \), \( Z_{A,B} \approx 0.5109 \, \Omega \), and \( Z_{B,C} \approx 0.5909 \, \Omega \). During the fault emulation, the impedances of the phases \( A \) and \( B \) become \( Z_{A,B} \approx 0.4896 \, \Omega \) and \( Z_{B,A} \approx 0.4812 \, \Omega \), as shown in Fig. 4(e). The reduction of these grid impedances is due to the interconnection of the two-phase resistive load at the PCC. Also, the power angles of the PCC are presented here individually for each phase, as depicted in Fig. 4(f). Initially the power angle of each phase were \( \phi_A \approx 0.02296 \, \text{rad} \), \( \phi_B \approx 0.0298 \, \text{rad} \), and \( \phi_C \approx 0.03852 \, \text{rad} \). During the fault occurrence, these power angle suffered deviations and became \( \phi_A \approx -0.00275 \, \text{rad} \), \( \phi_B \approx 0.0076 \, \text{rad} \), and \( \phi_C \approx 0.02846 \, \text{rad} \), respectively.

In comparison with the three-phase fault experiment, the present experiment depicts some interesting aspects that could be used to distinguish both events. The two-phase fault produces asymmetric undervoltages that can be observed by the increase of the PCC unbalanced degree. Moreover, this unbalanced condition can also be detected by monitoring the grid impedances and power angle estimation that present different deviations for each PCC phase.

7.3. Scenario III - open-circuit fault emulation

Open-circuit fault conditions also generate asymmetries on the power grid. For that reason, this operational condition is also tested to evaluate the performance of the proposed WB-HIDS. The controlled switch \( S_4 \) provides the emulation of this fault condition by disconnecting the phase \( A \) of the PCC for a period of \( \Delta t \approx 1 \) s. Fig. 5(a)-(f) show the experimental results obtained from this operational scenario. The open-circuit fault emulation is inserted at \( t \approx 0.93 \) s, generating an overvoltage of \( \Delta V_{A} \approx 170 \, \text{V} \), as shown in Fig. 5(a). It extrapolates the wavelet coefficient energy allowed limit of (21), triggering the WB-HIDS, as depicted in Fig. 5(b). During the fault occurrence, the unbalanced degree raises to \( \Delta_{\omega} \approx 28.8\% \), as presented in Fig. 5(c), characterizing a severe unbalanced condition. Also, the estimated frequency of the power grid ranges from 59.84 Hz to 60.15 Hz, as presented in Fig. 5(d). The grid impedance of PCC phase \( A \) increases to \( Z_A \approx 8.98 \, \Omega \), according to Fig. 5(e), while the power angle is reduced to \( \phi_A \approx -0.0042 \, \text{rad} \). The impedance variation observed in this experiment extrapolates the limit imposed by the standard PREN 50330–1 (see Table 2). However, the system under test is a three-phase microgrid, and could not be analyzed by using this constraint. In comparison with the tests realized before, the set of data has different aspects that permit the proposed method to classify and provide important issues for detecting fault or islanding conditions.

7.4. Scenario IV - PV system islanding emulation

In this experiment, the effectiveness of WB-HIDS to evaluate islanding conditions was verified. The PV system employed in this experiment operates as a controlled current source (i.e., grid-feeding converter) and could not operate in islanding mode. Therefore, to
emulate the islanding condition, controlled switches $S_1 - S_6$ were employed for inserting an external impedance $Z_{ext}$ (three-phase resistor branch of $r_{ext} = 7.0$ $\Omega$) between the PV system and the PCC (see Fig. 1). The insertion was implemented at $t \cong 0.68$ s and remains linked for more than 2 s.

Fig. 6(a)-(f) present the experimental results obtained from this operational scenario. All the experimental results are presented for phase A of the PV system. The emulation of the islanding condition at the PV system produces an overvoltage $\Delta V_{sA} \cong 45$ V, as shown in Fig. 6(a). This voltage deviation is enough to provoke the energy coefficient extrapolation depicted in (21), which triggers the WB-HIDS, as presented in Fig. 6(b). This operational condition modifies the unbalanced degree slightly to $\Delta_{un} \cong 0.4\%$, as depicted in Fig. 6(c). The system frequency deviates from 60.03 Hz to 60.17 Hz, as presented in Fig. 6(d). The estimated impedance and power angle range from initial values of $Z_{d} \cong 0.508$ $\Omega$ and $\phi_1 \cong 0.02319$ rad to $Z_{d} \cong 7.45$ $\Omega$ and $\phi_1 \cong 0.01694$ rad, as presented in Fig. 6(e) and 6(f).

According to the Table 2, two significant deviations overtake the constraints imposed by the standards. In the first, the PCC voltage amplitude extrapolates the upper limit imposed by the IEEE Std. 1547. In the second, impedance estimated value overcome the limits established in PREN 50330–1. Associated with the time duration of the event, it characterizes an islanding condition and differs from the fault scenarios presented before.

7.5. Scenario V - HPE disconnection

This experiment evaluates the performance of the proposed WB-HIDS when HPE is disconnected from the PCC. Controlled switch $S_7$ implements the islanding condition of this DG (see Fig. 1) at $t \cong 1.1$ s. Fig. 7(a)-(f) present the experimental results of this islanding emulation. The disconnection of the DG causes an undervoltage of $\Delta V_{sA} \cong 2.5$ V at the PCC, as shown in Fig. 7(a). This voltage deviation is enough to extrapolate the allowed limit imposed in (21), triggering the WB-HIDS, as presented in Fig. 7(b). The unbalanced degree remains almost constant during the event as presented in Fig. 7(c). The system frequency varies from 59.98 Hz to 60.09 Hz as shown in Fig. 7(d). The grid impedance ranges from $Z_{d} \cong 0.529$ $\Omega$ to $Z_{d} \cong 0.415$ $\Omega$, as depicted in Fig. 7(e). The power angle also varies from $\phi_1 \cong 0.02902$ rad to $\phi_1 \cong 0.01967$ rad, as presented in Fig. 7(f).

In comparison with the experiments realized before, the deviations are smaller because the power rating of the DG is approximately 1/5 of the power grid and 1/3 of the PV system. For that reason, the islanding condition could not be detected by using the standard constraints presented in Table 2. However, the proposed WB-HIDS provides power quality indices coherent with the event. It means that for power correlation, the power quality indices generated by the proposed WB-HIDS will agree with the standard limits mentioned in Table 2.

8. Conclusion

This paper presented a wavelet-based hybrid system (WB-HIDS) for detecting islanding conditions in ac microgrids. The implementation of the WB-HIDS employs a modified CWT algorithm, also introduced in this work, for accomplishing its real-time implementation (RT-CWT). The use of the RT-CWT improves the non-stationary signal analysis for generating power quality-related indices. The identification of islanding patterns is performed through the analysis of a data set composed of power quality indices, such as voltage amplitude, event duration time, unbalanced degree, system frequency, grid impedance, and power angle. The power quality issues related to the signal injection was mitigated by using a transient detection scheme that limits the duration of the interharmonic injection and its implementation only when a transient has occurred, which mitigates the disturbance provoked by the ADM approaches. The estimated power quality indices provided by the WB-HIDS were analyzed and compared with the limits set up on the standards or system power rating, for detecting an islanding condition or fault occurrence. The use of various power quality indices simultaneously also minimizes the NDZ error related to the PDM schemes. Operational scenarios such as short-circuits (two and three-phase faults), open-circuit, and islanding occurrence, were accomplished in an experimental ac microgrid to evaluate the effectiveness of the proposed method. Faults produced significant variations in all estimated indices and presented patterns different in comparison with the islanding cases. The proposed WB-HIDS presented an expected performance for detecting islanding conditions and distinguishing this event from possible fault occurrences.

CRediT authorship contribution statement

Sâmara Cavalcante Paiva: Methodology, Software, Validation, Formal analysis, Data curation, Investigation, Writing - original draft. Ricardo Lúcio de Araujo Ribeiro: Conceptualization, Resources,
Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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