REVIEW OF ANTI-ISLANDING METHODS FOR GRID-TIED PHOTOVOLTAIC INVERTERS

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Abstract— Distributed generators based on grid-tied inverters must comply with a set of requirements so that they can operate according to security measures imposed by certifying entities. One of the essential requirements is non-operation in islanding situations. Solutions have been developed to remedy this type of operation. Through this work, the primary methods found in the literature are presented to serve as a starting point for researchers interested in this area.

Keywords— Islanding detection, PV inverters, Protection, Renewable energy

1 INTRODUCTION

The connection of photovoltaic (PV) inverters to the utility grid has to respect a list of prerequisites: voltage and current levels, total harmonic distortion (THD), islanding detection methods (IDM), and so on. Usually, PV inverters are current-controlled converters, and the utility grid operator should control the utility grid voltage (Remus Teodorescu, 2011; Reigosa et al., 2017a). However, if the main switch breaker isolates part of a circuit that has distributed generation (DG) and loads, and there is no power imbalance, the system may reach a stable point and does not shut down, which is not permitted by ongoing standards (Estebanez et al., 2011; Remus Teodorescu, 2011). This scenario is known as islanding. If this happens, the utility operator does not guarantee the power quality of the energy that is being fed to the islanded loads (Remus Teodorescu, 2011). Hence, the inverter must stop injecting active power into the utility grid.

When the normal operation of the distributed system is restored, the inverter can start operating again. The reconnection of the inverter is done after 3 minutes according to standards. There are two keywords related to islanding: intentional and unintentional islanding (Deshbhratar et al., 2016; Haider et al., 2018). Intentional islanding describes the planned isolation of the grid for maintenance purposes or scheduled operation in isolated mode (Deshbhratar et al., 2016). However, unintentional islanding happens due to grid malfunction (Haider et al., 2018).

The IDMs are classified into three main groups: remote-based, local and signal processing methods (Estebanez et al., 2011; Marchesan et al., 2016; Cao et al., 2016). Communication-based methods are an attractive solution. However, their implementation is complicated, expensive and impractical to be installed into the distribution system. The solutions using this kind of approach are power line communication, supervisory control and data acquisition (SCADA) and transfer trip (Guha et al., 2015). Other alternatives are local methods that are embedded into the PV inverters. The local methods are split into active and passive techniques (Lopes and Sun, 2006). The objective of this paper is to present the advantages and disadvantages of the main methods that have been studied in the last decades.

This paper is structured as the following. Section 2 presents a review of the remote and local methods, describing their characteristics and operation. Section 3 shows the experimental verification. In the end, the most important conclusions are highlighted.

2 ISLANDING DETECION METHODS

This section presents the main advantages and disadvantages of the most used IDMs found in the literature. The object is to show how important these methods are for the right protection of distributed generation. Without them, utility grid personal and equipment are vulnerable to possible islandings (Liu et al., 2010). The most common IDMs are presented in Table 1 and 2.

The IDMs may be classified by the variable that they use to identify possible islanding, for example, voltage-, frequency-, phase angle-, harmonic- and impedance-based variables (Cao et al., 2016). Some parameters are used to determine the performance of the protection methods. Detection time, power quality, reliability, and non-detection zone (NDZ, described in the next section) are the main parameters (Singam and Hui, 2006). Other features can also be considered. The cost is paramount when the PV inverter is going to be commercialized (Singam and Hui, 2006). So the method must not, ideally, consume too much computational processing to reduce cost in digital signal controllers. The IDMs may not work well when operating in a grid with high penetration of inverters (Cao et al., 2016). For last, the method may have a negative impact on the grid, reducing the power quality (Blackstone et al., 2012).

2.1 PASSIVE METHODS

Passive methods do not apply any disturbance to the utility grid (Singam and Hui, 2006). Its approach is only the monitoring of some parameters of the distribution system, such as current and voltage (Robitaille et al., 2005; Hatata et al., 2018).

However, this type of technique has a high NDZ (Massoud et al., 2009; Merino et al., 2015), with a probability of 30% of the islanding being in the region of non-detection (Guha et al., 2015). The term NDZ relates the area described by the reactive and active power mismatch in which the method does not detect islanding conditions (Zeineldin and Kennedy, 2009; Velasco et al., 2010). The use of advanced signal processing tools may reduce NDZ for passive methods: short-time Fourier transform and Wavelet transform (Do et al., 2016). The passive methods can be evaluated through the $\Delta P vs \Delta Q$ space.

2.1.1 Over/Under voltage and Under/Over frequency methods

Electrical power systems shall ensure acceptable levels of voltage and frequency. For this, one has to use large synchronous generators that maintain such stable levels. These must be respected so that the equipment connected to it can function satisfactorily. PV inverters use voltage and frequency as parameters to define their mode of operation (Severo, 2011; Kunte and Gao, 2008). If these parameters comply with the standards, the PV inverter usually operates adequately (Datta et al., 2014). However, if the values are out of acceptable range, it must stop supplying active power to the point of common coupling (PCC).

The method becomes unreliable in situations where not only the active power but also the reactive power consumed by the load equals the power supplied by the generators at the time of islanding (Datta et al., 2016). Thus, for this technique, the NDZ is very large (Severo, 2011). Employing IEEE 1547.2-2008, PV inverters connected to the grid must contain these two protections (Severo, 2011).

As advantages, this method has a simple implementation, not harming its efficiency when there are a multiplicity of inverters (Severo, 2011). The injected energy is not degraded, not compromising the dynamics of operation of the inverter. Therefore, it is necessary to use other techniques in partnership with this (Severo, 2011).

2.1.2 Phase angle jump detection methods - PJD

The PV inverter has already embedded in its control resources to detect the phase, frequency, and magnitude of the voltage seen in the PCC (Yazdani and Iravani, 2010). This information is of great importance in the implementation of the PJD. Its operation consists in detecting the phase difference between the injected current and the output AC voltage (Yazdani and Iravani, 2010). The next step is the comparison of the verified difference with the predefined limits. If the phase jump exceeds those limits, the inverter shuts down (Severo, 2011). The method stands out for its ease of implementation. The implementation is possible because the inverter has phase-locked Loop (PLL) methods for synchronization with the utility grid (Singam and Hui, 2006).

The passivity of the method allows the maintenance of the conversion efficiency by not presenting additional perturbations (Severo, 2011). This feature provides its use in a distribution network with high penetration of inverters as it does not affect the quality of energy and does not cause interference between the elements that compose the electric network (Paiva et al., 2014). However, its use can generate false failures by the difficulty of adjusting the pre-set phase reference limits when transients are caused by electric motors (Severo, 2011). It is noteworthy that small limits can leave the method very susceptible to noise, causing false detections (Severo, 2011).

2.1.3 Harmonic-based methods

The use of harmonic-based methods can follow two fronts: THD or specific harmonic. Typically, the first three harmonic components are used: third, fifth and seventh (Datta et al., 2016; Merino et al., 2015) in the islanding algorithm. However, its operation can be degraded by non-linear loads connected to the PCC, which makes it difficult to choose the correct detection limits.

The high penetration of inverters in an isolated area can also cause problems, as there is an absorption of harmonics by the converter itself, which can create false islanding detections (Reigosa et al., 2017a).

2.1.4 Impedance-based methods

The observable impedance at the output terminals of the DG can be used by passive techniques. The high switching frequencies of the inverter's electronic switches flow through the low impedance of the electrical network (Guha et al., 2015). When islanding occurs, the switching harmonics flow through the isolated load impedance that is usually much higher than the line impedance. This natural effect makes it possible to estimate

Table 1: Passive and active methods.

Passive method	Approach	Active method	Approach
Under/Over voltage	voltage-based	AFD	frequency-based
Under/Over frequency	frequency-based	SFS	frequency-based
Phase Jump Detection	phase angle	AFDPCF	frequency-based
Rate of change of frequency (ROCOF)	frequency-based	SMS	Phase-angle
Rate of change of active power	power-based	VPF	Voltage-based
Rate of change of frequency over power	frequency-based	Reactive Power Variation	Power-based
Rate of change of phase difference	phase-based	Harmonic-based	Harmonic injection
Voltage unbalance	voltage-based	Impedance-based	Harmonic injection
Total harmonic distortion	harmonic-based		

the output impedance of the converter (Guha et al., 2015). Harmonic-based methods use signal processing techniques in their implementation: fast Fourier transform (FFT), discrete Fourier transform (DFT) and wavelet transform.

2.2 ACTIVE METHODS

The active methods cause controlled perturbation as a way of detecting islanding conditions (Liu et al., 2010; Massoud et al., 2009). However, these methods deteriorate the power quality of the distribution system and increase the complexity of the inverter's control (Estebanez et al., 2011). Depending on the penetration of inverters working in parallel, the utility grid may become unstable (Cao et al., 2016).

2.2.1 Active frequency based methods

The active frequency drift method (AFD) is a technique that appears in many studies (Lopes and Zhang, 2008). The method does not operate with any feedback. Their approach consists of inserting a zero segment, represented by δf, in the negative and positive half-cycles in the current injected by the photovoltaic inverter (Lopes and Zhang, 2008). The AFD method can be approached through two ways: positive and negative chopping factor. The use of this factor with positive values causes frequency increase in the PCC, while the contrary choice for the chopping forces the decrease of the current frequency of the photovoltaic generator.

In both cases, the objective is to ensure that frequency passes the intervals defined by the regulatory authority. Thus, the inverter will disconnect with success from the power grid (da Silva, 2016; Severo, 2011). To improve its detection, the AFD with positive feedback (AFDPF), also known as Sandia frequency shift (SFS) has implemented a positive feedback (Lopes and Zhang, 2008). The frequency perturbation varies according to the frequency change measured by the PLL method. Its efficiency for operation when having a multiplicity of inverters is improved over AFD.

2.2.2 Voltage-based active methods

Another approach is to disturb the output voltage of the converter. For this, the reference current of the converter varies according to the following techniques. In (Cardenas et al., 2009), the effective voltage variation seen in the PCC is used. This variation is applied in a positive feedback algorithm, in which its value is amplified to increase the reference power error of the converter (Cardenas et al., 2009). In normal operation, this error is maintained in low values, but in moments of islanding, the error increases to allow the detection of islanding (da Silva and Komatsu, 2015).

2.2.3 Harmonic-based active methods

In (Hamzeh et al., 2016), the disturbance is made by means of a specific harmonic current. The goal is to change the equivalent impedance at the output of the inverter. The disturbance is not done consistently, but rather at defined intervals. This approach was chosen to reduce the impact on energy quality. This method guarantees non-interference between inverters, which ensures the operation for networks with multiple inverters. In (Reigosa et al., 2017b), the proposed method consists of injecting a high-frequency signal into a micro-frame when there are multiple inverters.

A strategy of a system operating with coordination is made to avoid that there is possible interference between the static converters. In (Cai et al., 2013), there is a complete work, showing the need to use two harmonic injection when there is an unbalanced impedance network for three-phase systems. The purpose of this work is to prove that the injection of only one harmonic is not sufficient for the correct calculation of the impedance for an unbalanced impedance network.

2.2.4 Impedance-based active methods

The impedance-based islanding detection method at a certain frequency considers the harmonic content caused at the voltage of PCC. In some situations, in which the electrical network presents impedance lower than the load at a desired harmonic frequency, the utility grid absorbs this harmonic spectrum by imposing the path of least effort to the current. Thus, to determine the amplitude of the harmonic voltage chosen, simply multiply the impedance of the load by the current at the

Table 2: Computational-,transform- and communication-based methods

Computational-based	**Transform-based**	**Transform-based**	**Communication-based methods**
Artificial neural network	Fourier	Wavelet	Transfer trip
Machine learning	Discrete Fourier	Morphological gradiant wavelet	SCADA
Decision trees	Fast Fourier		Remote-end measurements
Probabilistic neural	S transform		Power line signaling scheme
Fuzzy logic control	Hyperbolic S		
Data mining	TT		
Bayes classifier	Empirical mode decomposition		
Support vector machine	Hilbert Huang		

same harmonic frequency of the voltage (Bower and Ropp, 2002).

Since the method encompasses the shortcomings of the harmonic detection method, one can use subharmonics as a solution. However, its amplitude must be low to the point of possible problems in transformers and components connected to the power grid in the same PCC. In cases where there is a multiplicity of inverters, the harmonics injected for detection by the method can not be used by all inverters, because even at low impedance, all the harmonics imposed by the inverter network are added, which can cause false detection of islanding (Bower and Ropp, 2002).

In (Sumner et al., 2001), to estimate the impedance it is used the injection of a voltage by means of the inclusion of an inductor. The generated current is used to evaluate the impedance seen at the output of the converter. In (Ciobotaru et al., 2007), the impedance estimation is accomplished by means of the active and reactive power variation. This method needs a good PQ control in order to generate the disturbances and thus estimate the value of the impedance at the output of the inverter.

2.2.5 Reactive power variation

The method of reactive power variation (RPV) is based on the injection of disturbances in the reactive power reference to modify the point of operation of the frequency in islanding conditions (Chen and Li, 2016). The perturbation can occur in unilateral or bilateral direction. The signal injection direction represents whether the inverter is absorbing or supplying reactive power.

In (Zhu et al., 2013), the unilateral perturbation is used, whereas in (Zhang et al., 2013), it proposes both directions for islanding detection. However, (Chen and Li, 2016) shows that they do not operate to the satisfaction of multiplicity of inverters. To solve such a problem, two forms of perturbation are used, one less intense and one more intense to ensure that the inverter can detect the grid fault.

2.3 COMMUNICATION-BASED METHODS

Communication-based methods include transfer trip, power line signaling scheme, and SCADA (Singam and Hui, 2006). The use of transfer trip requires reliable breakers and reclosers which can be accomplished through SCADA. The Power Signaling scheme uses the distribution grid to apply a signal. This signal is read using a local receiver included in the inverter. If the receiver no longer detects the presence of the signal, the inverter disconnects itself immediately (Mahat et al., 2008). The choice of frequency of the signal injected for communication should be made with caution.

There may be elements in the electrical network that cause signal attenuation, such as inductors (Guha et al., 2015). Care should be taken with the use of the same frequency that is already being used by other equipment to avoid interference citebib:Chen. This method is reliable but not feasible for small generators because its implementation is costly (Guha et al., 2015; Yu et al., 2010).

3 EXPERIMENTAL VERIFICATION

The main objective of this section is to show how a conventional PV inverter operates when connected to the utility grid and an example of the detection of islanding by the inverter's protection. The two-stage topology uses a boost converter and a full bridge inverter. The boost converter uses a P&O maximum power point tracking (MPPT) method to extract the maximum power of the PV modules. The full bridge inverter has to transform the DC energy to AC energy to inject into the utility grid.

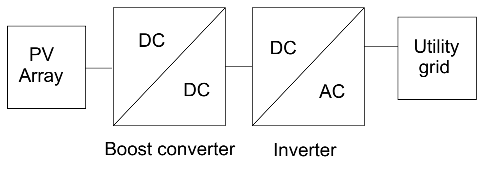

Figure 1: Two-stage single phase PV inverter connected to the grid.

The operation of the two-stage single-phase photovoltaic inverter is shown in Fig. 2.

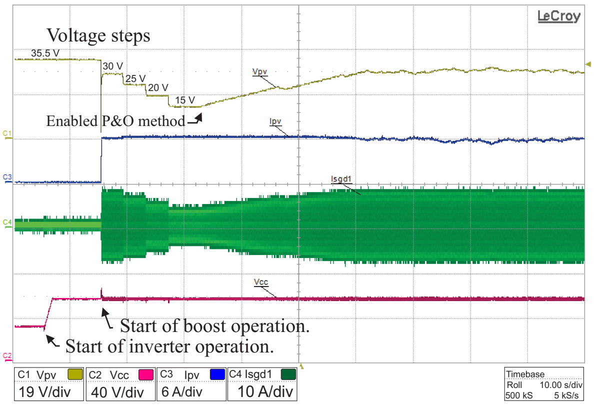

Figure 2: C1: Photovoltaic voltage (Vpv), C2: DC link voltage (Vcc), C3: Photovoltaic current (Ipv) e C4: Current (Isgd1) injected by SGD1 (Distributed generator 1).

Fig. 3 shows the disconnection of the inverter with the Under/Over frequency and voltage methods in the worst case ($\Delta P = 0$ and $\Delta Q = 0$). One sees that the system keeps injecting power into the islanded load. The voltage and frequency are kept the same before and after the islanding. So it is paramount to use robust techniques to avoid the islanding of the DG. All the experimental tests used the ABNT NBR IEC 62116 standard.

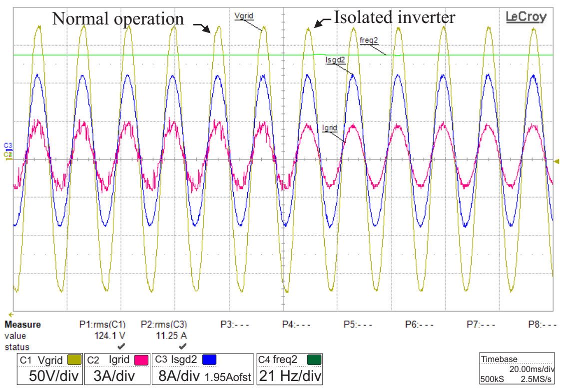

Figure 3: C1: Utility grid (V_{grid}), C2: Grid current I_{grid}, C3: Injected current (I_{sgd2}) e C4: Frequency injected by SGD2 (Distributed generator 2) - experimental result.

One sees in Fig. 4 a zero segment in the output current of the PV inverter. The AFD and SFS techniques use this approach. The increase in frequency imposed by the active perturbation forces the frequency to drive away to reach the upper-frequency threshold. However, several references prove that the chopping factor of those methods has to be chosen in a way that respects the standard requirements, such as THD less than 5% (IEEE STD 1547). When the method is evaluated in a high penetration of inverters the method may cause false tripping or turn unstable the utility grid due to the increase in the THD.

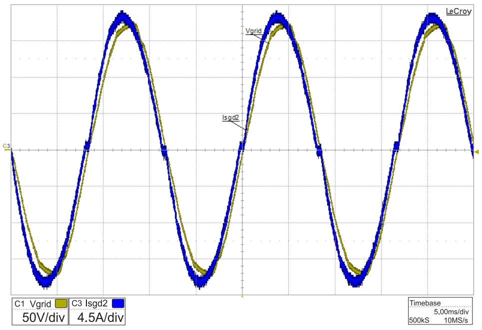

Figure 4: C1: Utility grid (V_{grid}), C2: Injected current I_{sgd2}. Active frequency drift method - experimental result.

Figs. 5 and 6 present the response to islanding of the AFD and SFS methods. The former takes around 38 grid cycles to deviate the frequency and detect islanding. However, the SFS can detect islanding in 26 cycles. These results were obtained with the connection and islanding only with one inverter and the local load.

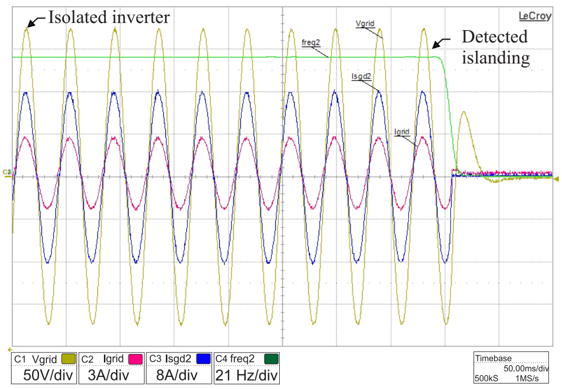

Figure 5: C1: Utility grid (V_{grid}), C2: Grid current I_{grid}, C3: Injected current (I_{sgd2}) e C4: Frequency injected by SGD2 (Distributed generator 2) - experimental result.

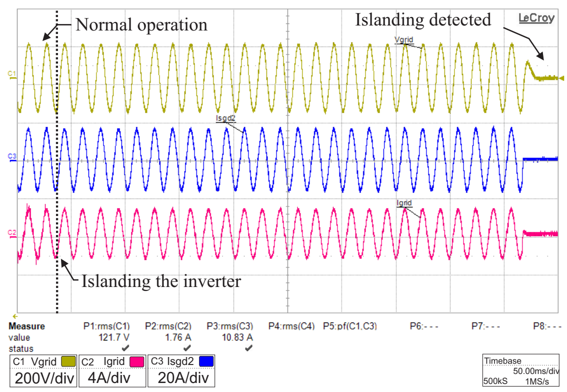

Figure 6: C1: Utility grid (V_{grid}), C2: Grid current I_{grid}, C3: Injected current (I_{sgd2}) - experimental result.

4 CONCLUSIONS

There is a great need to increase the robustness of the IDMs commonly used in commercial applications. A set of methods that guarantee the protection of photovoltaic generators was briefly presented. The experimental results presented in the result section are used to demonstrate the importance of the IDMs. One notices it is not easy to select the most appropriate method for given network topology, and further studies are required.

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