Analysis of Synchronization and Islanding Detection Methods for Single-Stage Microgrids

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Abstract- Synchronization and islanding detection represent some of the main issues for grid-connected photovoltaic systems (PVSs). The amount of distribute generation connected to the distribution network is increasing. The synchronization technique allows to achieve PVS high power factor operation and it provides grid voltage a combined review is advantageous. To use this resource more effectively, splitting of the distribution network, or islanding the system, for prevention of power outages is being considered by some utilities. . The islanding detection control function ensures safe operation of the PVS. Focusing on low-power single-stage PVSs, in this study the most adopted and the highest performance synchronization and islanding detection methods are discussed. The role of the synchronization system is fundamental to detect the grid conditions, for the islanding detection purpose, and to manage the reconnection to the grid after a PVS trip. avoids out-of synchronism re-closure is proposed. The island is kept in synchronism with the rest of the utility while it is not electrically connected. This is referred to as synchronous islanded operation. A phase difference control algorithm, developed by the authors, was tested in a single set scenario on a 50-kVA diesel generator using two different governors. These are the "standard product" variable gain governor of the diesel generator and a governor developed by the authors, which utilizes supplementary inputs in addition to engine speed.

Indexed Terms- photovoltaic systems; synchronization systems; phase locked loops; islanding detection methods

I. INTRODUCTION

Due to the photovoltaic prize reduction and availability of loan products, a significant portion of PVSs have been recently installed also in absence of governments initiatives especially for residential applications. A performance evaluation of residential PVSs in some European countries is presented in [4]. Considering the period 2014–2016, the highest specific yield in kWh/kWp has been registered in Italy in 2015.

The PVSs inverters price has diminished around In addition, the design optimization of the PVS converters has facilitated the reduction of the total cost of ownership [6]. Nevertheless, the increase of PVS grid-connected installations implies several management challenges depending also on the point of interconnection between the PVS and the grid [7–10]. In this scenario advanced control features of the PVS inverters can contribute to overcome some of the grid management challenges due Looking at the residential applications, the PVSs can be single-stage or double-stage. In case of single-stage PVSs, the PV array is directly connected to the inverter avoiding a boost DC/DC converter.

Single-stage transformer less PVSs represent the most promising technology due to lower weight, higher efficiency, smaller size and limited cost than double-stage PVSs or single-stage architectures coupled to low-frequency transformers Focusing on a single-stage PVS, a review about some of the main control issues is presented in [19], however the analysis is limited to current and voltage control methods and maximum power point tracking (MPPT) techniques. About the most important issues to be considered in grid-connected PVS there are the synchronization with the grid and the detection of the islanding condition. Synchronization deals with PVS high power factor operation, since the synchronization algorithms objective is to provide grid voltage information about amplitude, phase and frequency in order to generate a current/voltage reference which is in phase with the grid voltage.

Synchronization deals also with the grid voltage monitoring. According to the grid-connection requirements [25], the PVSs connected to the low-voltage distribution grid must operate without causing step change in the RMS voltage at the point of common coupling (PCC) exceeding 5% of rated value. In addition, the synchronization parameters limits for grid-connected PVS are: 0.3 Hz for the frequency difference, 10% for the voltage difference. Abnormal conditions can arise on the utility grid which require a prompt response from the grid-connected PVS, hence the information provided by the synchronization system are fundamental for this purpose

Unintentional islanding phenomenon is verified in case of grid power outages when the PVS continues to supply the local loads. Unintentional islanding can cause damages to the local electrical loads, to the grid-connected PVS inverter, to the technicians during the maintenance operations. Numerous improved islanding detection algorithms have been proposed in literature in the last years aiming to detect islanding phenomenon in all possible cases. However, many these algorithms are not designed peculiarly for PVS.In case of low power residential PVSs and in particular in case of single-stage systems, the PVS inverter is commonly in charge of the islanding detection, hence the anti-islanding functionality represents one of the main challenge in the PVS inverters design [18]. The anti-islanding protections must be implemented on the basis of the international standards requirements for distributed power generation systems (DPGSs).

In particular, it is required that unintentional islanding be detected in less than two seconds as already established in the previous guidelines for PVSs. After a disconnection due to the islanding detection an improper reconnection event is not improbable if the PVS breaker connects the system to the grid when the PVS voltage is out of phase.

In this hypothesis a second disconnection can occur due to the PVS protections action. Hence the reclosing procedure has to be managed in strict coordination with the PVS synchronization system. For this reason, synchronization and islanding detection issues must be analyzed together.About synchronization systems some books have been published such as . Few review papers can be found in literature .

In all the main families of synchronization techniques (also including the artificial intelligence techniques) are classified showing advantages and disadvantages. Basic concepts about phase-locked loop (PLL) are explained in. Referenceis devoted to three-phase applications, reference is devoted to single-phase application, while is oriented to design issues.

About islanding detection methods many review papers have been published in literature considering different DPGSs . Reference provides a review of the islanding detection methods for high power DPGSs. In extensive review of the islanding detection methods is provided focusing on some performance indices evaluation and in particular on the detection time. Reference is focused just on passive methods, reference is focused just on active methods.

In the focus is on active and passive methods and a new active methods is proposed for a three-phase PVS. The same islanding detection methods are discussed also in also including the hybrid detection methods. However, hybrid methods are categorized just as combination of active and passive methods. Insome active islanding detection techniques are compared on the basis of a new index assessing the non-detection-zone (NDZ) size. In the active techniques are classified in two categories: techniques introducing positive feedback in the control of the inverter and techniques based on harmonics injection. In the islanding detection methods based on different signal This paper describes a technique to avoid out-of-synchronism re-closure to the main system, as was suggested in [5]. The islanded system is kept in synchronism with the rest of the utility by using a reference signal transmitted from a secure part of the network. Since the island is held in synchronism, it can be reconnected to the main system at any time with minimal transient effect.

This has the advantage that the islanded area is not limited in geographical size. Technical advancements in communications and phase measurement units (PMU) combined with the advent of fast digital governing of generation have been crucial in the formulation of this concept. For an island to be

sustainable, there must be sufficient distributed generation to supply the trapped load within the island.
The ability for the phase difference to be held constant in steady state and the restoration to an in phase condition following various load disturbances, have been investigated. Focusing on single-stage single-phase PVSs, the present study aims at giving an update of the most-recent trends about synchronization techniques and islanding detection methods, in particular: in Section 2 there are summarized the main goals of the single-stage PVSs control systems. The most adopted and the highest performance grid synchronization

II. CONTROL SYSTEM FUNCTIONALITIES OF SINGLE-STAGE PHOTOVOLTAIC POWER SYSTEM

The overall control structure of a single-stage PVS is shown in Figure 1 where it is assumed that the PVS can be connected to a local load, to the utility grid or it can be part of a smartgrid. The control functionalities can be classified in basic control functions and ancillary control functions. The basi control functions are the maximum power extraction, the grid synchronization, the current and the voltage control, the unintentional islanding detection. High power factor operation and harmonic rejection are achieved by proper design of current and voltage controllers and of the synchronization system. The current/voltage control reference signal is provided by the PV source power control which consists of a maximum power point tracking (MPPT) algorithm and a DC voltage controller. The MPPT algorithm is in charge of the maximum power extraction.

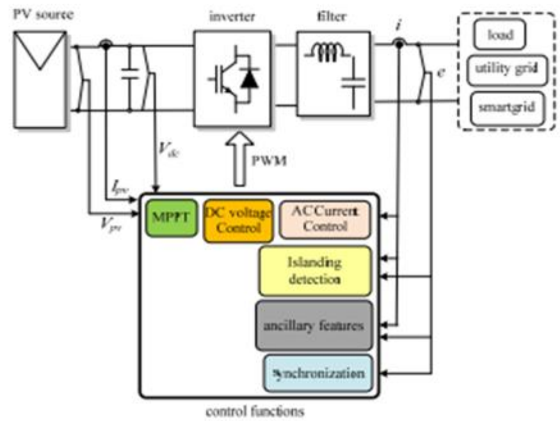


Figure 1. Single-stage photovoltaic systems (PVSs) control functions

The ancillary control functions are the ride-through capability, the voltage and the frequency support to the local loads or the main grid. The ancillary control functions are out of the scope of the present study.

III. GRID SYNCHRONIZATION

The phase angle of the grid voltage is a critical piece of information for grid-connected systems since it is used to obtain the control reference signal as previously pointed out. Numerous methods using different techniques for synchronization and grid-voltage monitoring have been presented in the technical literature about DPGS. Most of these studies are related to three-phase system than to single-phase applications. Some of the methods are not always categorized properly, thus leading to confusion. In order to clarify, the most used techniques can be organized as presented

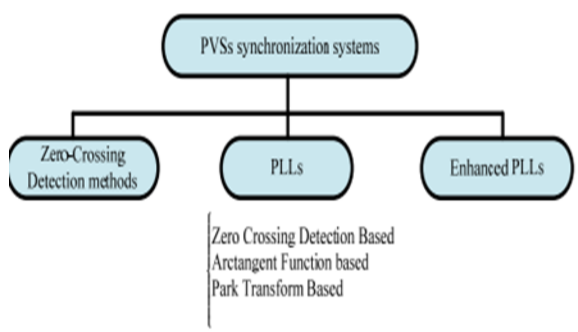


Figure 2. PVSs synchronization techniques classification.

Looking at the single-stage PVS shown in Figure 1, two synchronization systems are required in order to manage correctly the disconnections and reconnections with the main power system: the first synchronization system is used to monitor the voltage grid, the second one is used to monitor the PVS voltage. Among the synchronization systems presented in literature, only some methods are

3.1. Zero-Crossing Detection Methods

An elementary method used to extract information about phase and frequency of the grid voltage is based on the zero-crossing measurement. The ZCD structure is shown in Figure 3. When the grid voltage waveform crosses the zero, a counter provides in output information about the period and, consequently, the estimated frequency of the grid voltage is obtained. The phase θ of the grid voltage is achieved integrating Despite the simplicity, this technique does not allow high dynamic performances. Indeed, the phase tracking can be fulfilled just for each half cycle of the grid voltage waveform.

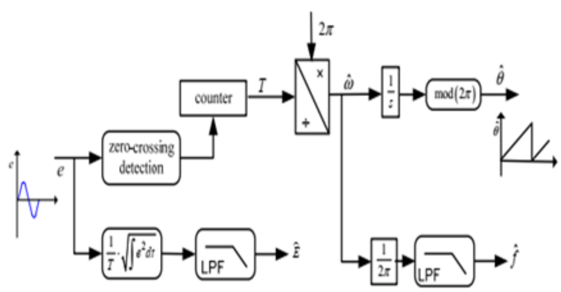
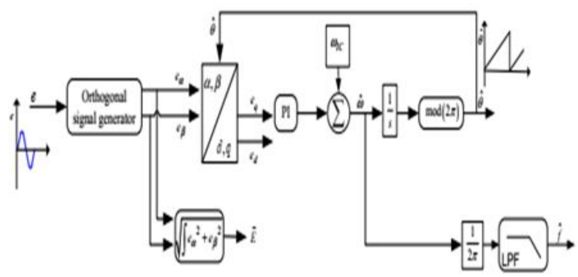


Figure 3. Zero-crossing detection (ZCD) structure.

Since the grid voltage *e* is generally affected by power quality disturbances, a low-pass filter (LPF) is used to extract the fundamental frequency *f*ˆof the original signal. No controller is employed in the detection and the method is not proper to track and to monitor the grid voltage in case of

3.2. PLLs

The PLL consists of a phase comparator and a PI controller. The phase comparator determines the phase error "which is provided in input to the PI. A reference frequency *IC* and the output of the PI are summed in order to evaluate the grid voltage frequency . The feed-forward action allows to improve the PLL dynamic performance. Later the grid voltage angle θˆ is calculated by the information of the grid voltage frequency. The phase comparator operation can be based on a reference signal provided by the ZCD of the input grid voltage, by the arctangent function of by the Park transform. In case of ZCD PLL, the ZCD discussed in the previous subsection is employed to extract the phase reference for the phase comparator . As described before, also this synchronization system is not proper to track the grid voltage in case of abrupt variations. However, the ZCD PLL provides better performance than the ZCD technique since the estimated angle θˆ is controlled in closed loop.Both the arctangent function-based PLLs and the Park transform-based PLLs require a voltage orthogonal system. In case of the arctangent function-based PLL, the phase reference for the phase comparator is extracted calculating the arctangent by *e*α and *e*β information. The disadvantage is that the arctangent function is not easy to implement.



In Figure 4 there is shown the structure of a PLL-based on the Park transform which represents the most adopted solution. provides better performance than the ZCD technique since the estimated angle is controlled in closed loop. Both the arctangent function-based PLLs and the Park transform-based PLLs require a voltage orthogonal system. In case of the arctangent function-based PLL [42,64], the phase reference for the phase comparator is extracted calculating the arctangent by *eα* and *eβ* information. The disadvantage is that the arctangent function is not easy to implement. In Figure 4 there is shown the structure of a PLL-based on the Park transform which represents the most adopted solution.

All the PLLs described up to now need a LPF as in case of the ZCD synchronization method. It occurs to extract the fundamental frequency $\hat{f}$ of the original signal *e* which is commonly affected by harmonic disturbances. Neglecting the LPF, the detailed structure of the PLL based on the Park transform is depicted in Figure 5 for a better understanding of how the phase comparator is obtained through the use of the Park transform

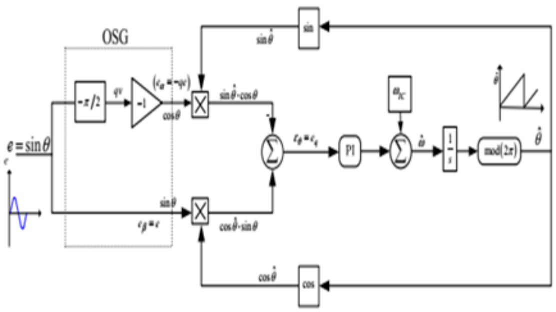


Figure 5. Detailed PLL structure based on the Park transform.

In case of single-phase systems, the orthogonal voltage system has to be artificially generated and it represents the main challenge for the grid voltage monitoring. The orthogonal signal generator (OSG) is in charge of the orthogonal voltage system realization. One of the most advanced technique adopts the second order generalized integrator (SOGI) . The OSG based on the SOGI filter allows also to extract the fundamental component of the grid voltage, for this reason the LPF used to extract $\hat{f}$ can be avoided in case of the SOGI PLL. The OSG based on the SOGI filter is shown in Figure 6 The grid voltage *e* is transformed in two sinusoidal signals denoted as *e'* and *qe'*. *e'* and *qe* are phase shifted of π/2. The sinusoidal signal *e'* is in phase with the grid voltage *e*. In addition, *e'* and the first harmonic component of the grid voltage exhibit the same magnitude

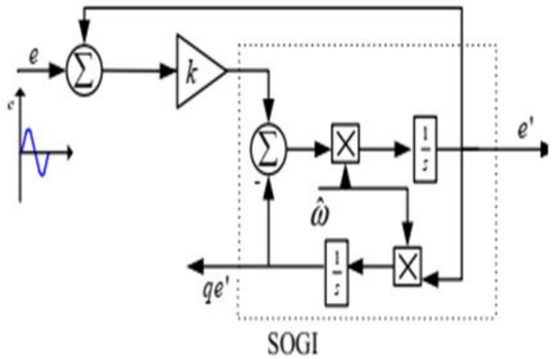


Figure 6. Orthogonal signal generator (OSG)–second-order generalized integrator

The SOGI acts like an infinite gain band-pass filter whose transfer function is defined as:

$$H_{SOGI}(s) = \frac{\omega_n s}{s^2 + \omega_n^2} \quad (1)$$

where !*n* represents the undamped natural frequency of the SOGI which should coincide with the estimated frequency (!*n* = . The performances of all the single-phase PLLs based on a OSG are particularly affected by the voltage offset commonly introduced by the measurement equipment and by the signal processing operation. The frequency of the error derived by the grid voltage offset is the same of the grid voltage waveform. The PLLs based on a OSG are not properly designed to provide rejection to the voltage offset. However, since the PI controller acts as a filter, the PLL controller parameters could be tuned in order to achieve filtering of the voltage offset. It would modify the bandwidth of the overall system, but, unfortunately, it would impact considerably the dynamic performances of the PLL. In [71] the performances of single-phase PLLs based on different OSGs are compared and a guideline for the PLLs parameters tuning is proposed

- *EPLLs*

In the last years, an alternative synchronization technique known as enhanced phase-locked loop (EPLL) has succeeded due to high filtering performance.

It consists of an adaptive nonlinear detection algorithm which provides two orthogonal signals synchronized with the grid voltage. The EPLL structure is represented in Figure It allows to estimate the frequency, the phase and also the amplitude *EEPLL* of the input signal fundamental component. The EPLL operates as an adaptive filter (either a notch or a band–pass filter) whose frequency tracks the fundamental frequency of the grid voltage. *eEPLL* denotes the filtered signal tracking the grid voltage supplied in input.

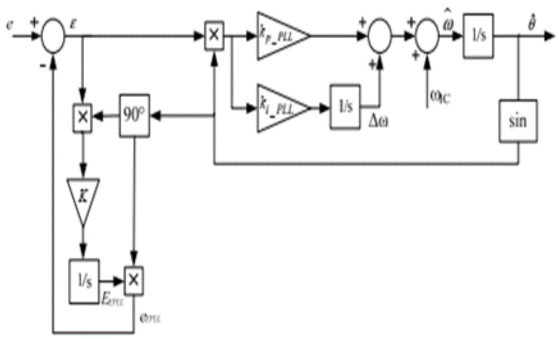


Figure 7. Enhanced phase-locked loop (EPLL) structure

The EPLL represents one of the most promising synchronization systems for single-phase applications since it provides: filtering capability in respect to the undesired harmonics, adaptive detection of the grid voltage fundamental frequency, proper estimation of frequency, angle and amplitude of the grid voltage supplied in input. Some modifications of the EPLL have been also proposed in the most recent literature, in particular in the structure of the EPLL has been modified in order to achieve a linear model.

The main differences of the EPLL compared to the PLL based on the park transform occur testing the two systems in presence of grid voltage perturbations, in particular frequency changes and harmonics. It has been demonstrated that the EPLL exhibits higher filtering capability and shorter transient. For all these reasons the EPLL represents the ideal candidate to operate in coordination with the islanding detection techniques discussed in the following Section

- Islanding Detection

In case of grid disconnection, the PVS operation depends on the power level provided by the PVS before islanding occurrence. In Figure 8 it is represented the PVS power stage for the islanding detection test. The grid utility breaker is denoted as Sg, two different breakers *S*1 and *S*2 are used to connect the PVS to the point of common coupling (PCC) and to connect the load. A variable RLC load is considered in order to assess the islanding phenomenon in case of different load powers and quality factors.

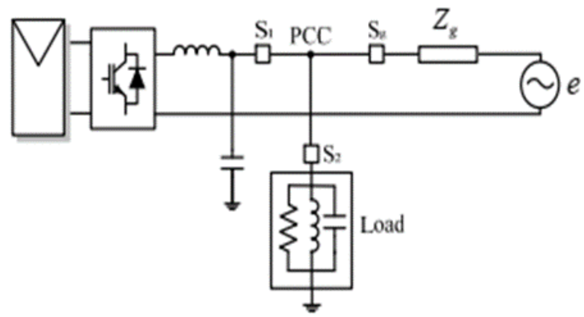
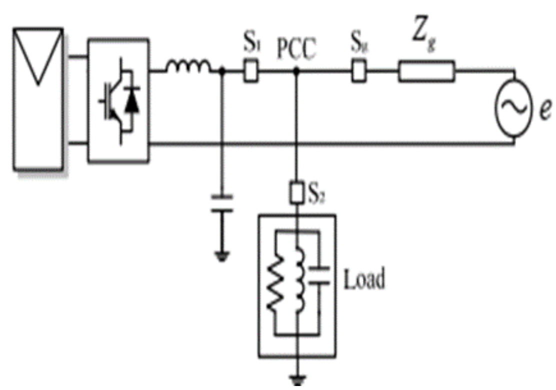


Figure 8. Photovoltaic system (PVS) power stage for islanding detection test.

For each islanding detection method, the non-detection-zone (NDZ) defines the area where the anti-islanding methods fail to detect islanding. As a consequence, the NDZ can be used as a performance index to assess the islanding detection methods. However, in comparison with the previous version of the standard [81], the new standard [25] requires voltage and frequency ride



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the standard, the new standard requires voltage and frequency ride-through capability of the PVSs which increases the NDZ of the islanding detection algorithms.

Hence it has to be pointed out that ride-through requirements hazard the islanding detection techniques. Traditionally the islanding detection methods were classified in remote techniques (based communication signals) and local techniques. Considering the recent advancements of communication equipment and the requirements updates related to the PVS standards, in this study a different classification is adopted. The islanding detection methods are classified in four main categories: Communication-based methods, passive methods and signal processing-based methods. In addition, in order to improve the performance of the islanding detection methods and to satisfy the standard requirements, hybrid techniques are developing in the last years which are based on combination of the previous categories. In Figure 9 the main islanding detection methods are summarized

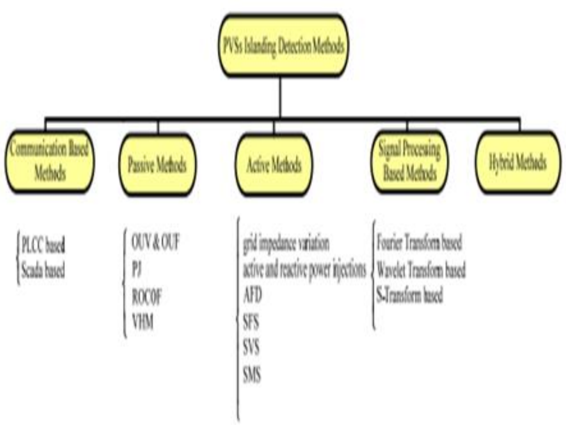


Figure 9. PVSs islanding detection methods classification.

4.1. Communication-Based Methods

Communication-based methods allow to achieve accurate and reliable assessment of the islanding conditions. Otherwise, considering the number of PVSs to be managed and the power size, the required equipment can vary. Hence these solutions are not common in case of low voltage and low power residential PVSs. The communication-based methods can be classified in: power line carrier communication (PLCC) methods, Supervisory Control Moreover, data acquisition (SCADA)-based methods

OUV and OUF Methods All grid-connected PVS inverters are required to have OUV and OUF protections. The aim is to avoid power supply by the PVSs when the voltage amplitude and frequency values at the PCC are different from set values Considering an RLC load whose resonant frequency is equal to the grid frequency, no reactive power absorption is verified by the load. In case of grid disconnection, the power absorbed by the load is equal to the active power provided by the PVS. Hence the RMS value of the voltage provided by the PVS at the PCC changes from *EPVS* = before the disconnection to

$$E_{PVS} = \delta E \quad (2)$$

where *E* is the rated RMS value of the grid voltage,

$$\delta = \sqrt{\frac{P_{PVS}}{P_L}} \quad (3)$$

PPVS is the active power supplied by the PVS, *PL* is the rated load active power. In conclusion the voltage value at the PCC increases or decreases depending on the PVS power generation. As a consequence, also the reactive power changes on the basis of the following relationship:

$$Q_{PVS} = \left(\left(\frac{1}{L\omega_{PVS}}\right) - C\omega_{PVS}\right)E_{PVS}^2 \quad (4)$$

In (4) *L* and *C* are the inductive and capacitive components of the RLC load, !*PVS* denotes the voltage frequency at the PCC after the grid disconnection. Hence it results

$$\omega_{PVS} = \frac{-\left(\frac{Q_{PVS}}{E_{PVS}^2 C}\right) + \sqrt{\left(\frac{Q_{PVS}}{E_{PVS}^2 C}\right)^2 + \frac{4}{LC}}}{2} \quad (5)$$

Similarly, small active and reactive power variations imply small voltage variations in terms of frequency and amplitude. For this reason, the OUV and OUF protection cannot detect islanding. OUV and OUF protections are considered insufficient anti-islanding techniques since the active and reactive power variations due to the islanding phenomenon are commonly limited and, as a consequence, there is high probability to fall into the NDZ. Rate of Change of Frequency Method The ROCOF islanding detection method measures the rate of change of frequency df/dt in a set time window. When the grid is disconnected, the power mismatch between generation and load causes frequency variations. The PVS is tripped when df/dt exceeds the threshold value. The threshold setting is the main issue of this method since it is necessary to distinguish islanding from load changes. Besides the ROCOF exhibits a wide NDZ combined with slow dynamics.

4.2.4. Voltage Harmonic Monitoring Method The voltage harmonic monitoring (VHM) method is based on the voltage harmonic distortion estimation to detect the occurrence of the islanding phenomenon . In grid-connected operation the voltage at the PCC is set by the grid, but, in case of grid disconnection, the PVS inverter determines the voltage at the PCC. Nevertheless, the voltage harmonic distortion varies with the grid impedance and it depends on the loads connected to the PCC. As a consequence, the accuracy of the method can be hazarded if the islanding detection thresholds are not properly set. Better performance can be achieved monitoring some selected harmonics variations rather than the overall voltage harmonic distortion.

In this hypothesis the harmonics variations can be detected by means of PLLs tuned in order to track the selected harmonic components.

4.3. Active Methods

The active islanding detection methods are developed with the goal to achieve better performance than the passive methods. The active methods introduce a perturbation in the PVS through the injection of an active signal The active signal injection is designed considering starting from ideal operating conditions of the PVS.

The main active methods can be classified in: Grid impedance variation methods, active and reactive power injections methods, active frequency drift (AFD), Sandia frequency shift (SFS), Sandia voltage shift (SVS), slip-mode frequency shift (SMS). 4.3.1. Grid Impedance Variation Methods Islanding phenomenon assessment can be based on grid impedance variations monitorin A small harmonic current component is drained into the PVS. The grid impedance is evaluated at the frequency of the injected harmonic component. Additional equipment can be employed to measure the grid impedance. Otherwise the grid impedance measurement can be embedded in the PVS inverter control system Active and Reactive Power Injections Methods

The rationale of the active power injections method is to use controlled active power injections causing active power variations D$PPVS$ in the PVS. Consequently, voltage variations can be observed exceeding the threshold voltage value of the islanding protections. Assuming a resistive load R, whose power PL is constant, it is possible to express the power provided by the PVS as function of the voltage at the PCC. In case of islanding condition, it results:

$$P_{PVS} = P_L = \frac{{E_{PVS}}^2}{R} \tag{6}$$

Hence it can be obtained:

$$\frac{\partial P_{PVS}}{\partial E_{PVS}} = 2 \cdot \frac{E_{PVS}}{R} = 2 \cdot \frac{\sqrt{R \cdot P_{PVS}}}{R} = 2 \cdot \sqrt{\frac{P_{PVS}}{R}} \tag{7}$$

The voltage variation can be evaluated as:

$$\Delta E_{PVS} = \frac{\Delta P_{PVS}}{2} \cdot \sqrt{\frac{R}{P_{PVS}}} \tag{8}$$

Similarly, reactive power injections can be used to cause reactive power variations D$QPVS$ in the system . As a consequence, frequency variations are obtained exceeding the frequency threshold value and islanding condition can be detecte

- Slip-Mode Frequency Shift

The slip-mode frequency shift (SMS) detects islanding phenomenon using positive feedback to lead the PVS towards instability in case of grid disconnection

In case of grid disconnection, the PVS frequency changes naturally. The PVS PLL action can be modified in order to increase the frequency rate of change rather than to annul it. The phase is forced to be a function of the voltage frequency at the PCC. The PLL acts to increase the frequency until the PVS inverter voltage phase grows faster than the phase of the RLC load (unstable region). The PVS is tripped when the inverter voltage frequency exceeds the threshold value. The method can fail when the load phase slope is higher than the slope achieved by the SMS technique. In this case instability could not be recognized.

In Figure 11 there is shown how the action of the PVS PLL is modified on the basis of the SMS rationale. The PVS phase angle changes from θˆ*PVS* to θ*SMS*

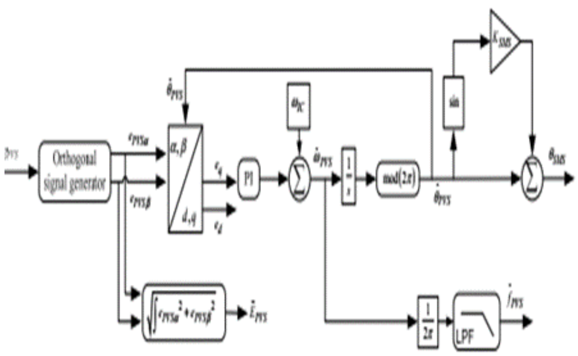


Figure 11. PVS PLL operation in case of SMS islanding-detection technique

4.1. Fourier Transform-Based Methods:
The PVS output power is typically affected by variations after grid disconnection, as a consequence, its spectrum varies with continuity in a certain frequency range. Fourier transform (FT) is not proper for the analysis of non-stationary signals. Hence it cannot provide information about fluctuating signals linked to the islanding occurrence [103]. For this reason, the application of this signal processing technique to the analysis of transient phenomena such as islanding is not very

4*.4. Signal Processing-Based Methods*
Signal processing techniques can be adopted to design new islanding detection algorithms or to improve the performance of the previous developed algorithms. The signal processing islanding detection methods are generally based on (a) Fourier transform; (b) wavelet transform and (c) S-transform. 4.4.1. Fourier Transform-Based Methods
The PVS output power is typically affected by variations after grid disconnection, as a consequence, its spectrum varies with continuity in a certain frequency range. Fourier transform (FT) is not proper for the analysis of non-stationary signals. Hence it cannot provide information about fluctuating signals linked to the islanding occurrence. For this reason, the application of this signal processing technique to the analysis of transient phenomena such as islanding is not very common. However, some islanding detection techniques based on the Discrete Fourier transform (DFT) and its modifications have been discussed in literature. In a modified VHM islanding detection technique is proposed. Since the equivalent harmonic components measured at the PCC change in case of islanding occurrence, the DFT is employed to assess harmonic components variations. Differently in a kind of FT, named Goertzel algorithm, is employed to develop an active islanding detection method where the Goertzel algorithm extracts the magnitude and phase of some selected components with limited computational burden.

- Synchronization and Islanding Detection Coordination

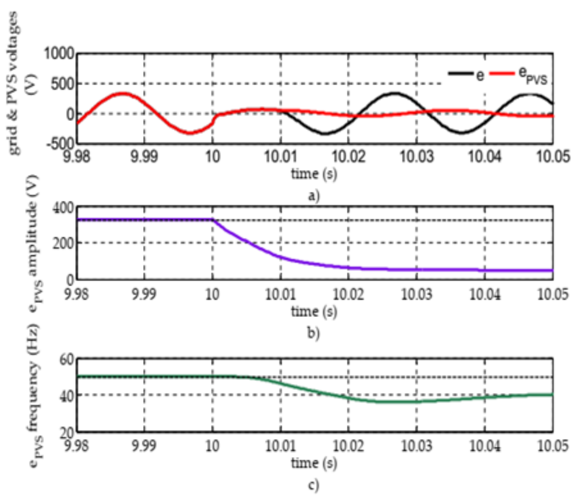
ZCD methods and ZCD-based PLLs exhibit low dynamic performance and are not suitable for grid voltage monitoring in case of abrupt changes of the grid voltage and power quality disturbances. Arctangent-based PLLs are not particularly widespread due to implementation issues. The PLLs based on Park transform and SOGI OSG, known as SOGI PLLs and the EPLLs represent the most promising synchronization systems for single-phase PVSs due to high filtering capability, also in presence of grid voltage harmonic distortion, accuracy and high dynamic performances also in case of grid voltage abrupt variations. SOGI PLLs and EPLLs are ideal candidates to be employed in the islanding detection and in the reconnection of a PVS to the main grid after an islanding event.

IV. RESULTS AND DISCUSSION

5.2. Reconnection of a PVS to the Grid after an Islanding Event

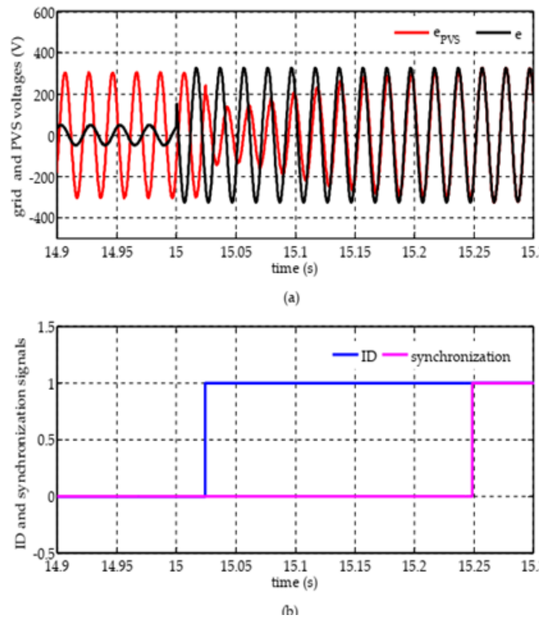
Independently of the adopted islanding detection technique, the reconnection of a PVS after an islanding event needs to be managed by two PLLS or EPLLs circuits. Indeed, an improper reconnection event is not improbable if the PVS breaker *S*1 connects the system to the grid when the PVS voltage is out of phase compared to the grid voltage. In this occasion over currents can be verified or, in the worst case, a second disconnection can occur determined by the PVS protections intervention. Hence the reclosing procedure has to be managed in strict coordination with the PVS synchronization system.

Assuming, for example, to detect the islanding condition using the active and reactive power injections method and to employ SOGI PLLs as synchronization systems, in Figure 12 there are shown the PVS voltage *ePVS* and the grid voltage *e* in case islanding occurs at *t* = 10 s. At this time, the grid utility breaker Sg is opened and during the islanding operation the amplitude and the frequency of the PVS voltage drift from the rated values



The information about the amplitude and the frequency of the PVS voltage, provided by the SOGI PLL, is employed to assess the islanding phenomenon within 2 s on the basis of the active and reactive power injections method.

The grid and the PVS voltage waveforms are not more synchronized and, when the *ePVS* amplitude and frequency deviations exceed the thresholds values, islanding is detected and also the PVS breaker *S*1 is opened. Denoting as *ID* the control signal providing information about the islanding condition, it is possible to define *ID* = 1 when islanding is not detected and *ID* = 0 when islanding is detected. Similarly, it is possible to use a control signal to assess synchronization of the PVS with the grid. In this analysis it is indicated with synchronization = 1 the condition when *ePVS* and *e* are in-phase, synchronization = 0 the condition when the two systems are not



synchronized. Assuming that the grid is recovered in few seconds, at *t*1 = 15 s the grid breaker Sg is closed again (Figure 13). Nevertheless, the reconnection of the PVS cannot be immediate. Since the grid and the PVS are not more synchronized after the islanding occurrence, some reconnection time is required. When the breaker Sg is reclosed, the control signal moves from *ID* = 0 to *ID* = 1. In the considered case study, the grid recovery is detected in less than 0.03 s, but the PVS is reconnected just at *t*2 = 15.25.

The PVS reconnection is possible only when *ePVS* and *e* are assessed again in-phase. In particular, the synchronization is detected when the phase and the amplitude difference between *ePVS* and *e* is null. Only at this time the synchronization control signal moves from synchronization = 0 to synchronization = 1.

In the described procedure two PLLs/EPLLs are required: one to monitor the PVS voltage and one to monitor the grid voltage. This example is provided to point out the role of the synchronization system and to demonstrate the need of a strict coordination between the islanding detection and the synchronization control units.

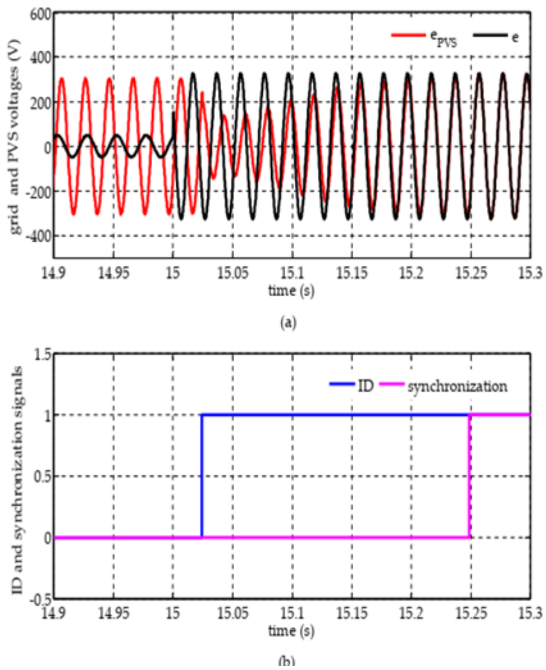


Figure 13. Grid and PVS voltages during resynchronization process. (a) *e* and *ePVS* waveforms; (b) ID and synchronization control signals

CONCLUSION

An extensive analysis of synchronization and islanding detection methods for single-stage PVSs is presented in this study. Synchronization and islanding detection represent some of the most important control issues for PVSs in the light of the new standards requirements. Abnormal conditions can arise on the utility grid which require a prompt response from the grid-connected PVSs, hence the information provided by the synchronization system are fundamental. Besides some islanding detection methods use additional PLLs for the harmonics monitoring. In other cases, the normal operation of the PLL is modified in order to detect the islanding phenomenon as it happens in case of the slip-mode frequency shift technique. Finally, it has to be considered that, after a disconnection due to the islanding detection, an improper reconnection event is not improbable if the PVS breaker connects the system to the grid when the PVS voltage is out of phase. In this hypothesis a second disconnection can occur due to the PVS protections action. Hence the reclosing procedure has to be managed with two synchronization systems.

There are, however, several other issues that must be addressed for the introduction of distributed generation and large-scale implementation of any islanding scheme. These are power quality, voltage regulation, avoiding unearthed operation, ensuring the correct operation of protection and safety of personnel. In addition, there are a number of challenges, specific to the proposed synchronous islanded operation, that require further investigation. scenarios, the effect of communications delay on system performance, co-ordination of protection systems, and identification of islanded operation.

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