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Islanding Detection Methods and Challenges for Distribution Generation: A Technological Review

Farshad Aslani [1], **Shuhui Li** [1], ***Senior Member, IEEE***
[1]Department of Electrical and Computer Engineering, The University of Alabama, Tuscaloosa, AL 35487

Corresponding author: Shuhui Li (sli@eng.ua.edu).

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ABSTRACT Islanding detection poses a significant technical challenge for the reliable operation of grid-connected photovoltaic (PV) systems, particularly as the deployment of distributed generation (DG) increases across modern power networks. An undetected islanding event may jeopardize the safety of utility personnel, degrade power quality, cause voltage and frequency instability, and lead to malfunction or damage of sensitive electrical equipment. This paper presents a structured and comprehensive review of local islanding detection methods (IDMs), which are categorized into three principal classes: passive, active, and hybrid approaches, with the associated challenges. Each category is examined in terms of its core detection principle and is evaluated based on key performance indicators, including detection time, non-detection zone (NDZ), threshold dependency, false and nuisance tripping probability, implementation complexity, and impact on system power quality. By comparing IDM performance across diverse operating conditions, analyzing implementation trade-offs, and synthesizing recent advancements, this review highlights key features, limitations, operational challenges, and emerging trends that affect the reliability of islanding detection. It aims to provide useful insights to assist researchers in selecting appropriate methods and in designing effective IDMs. Special emphasis is placed on the influence of evolving grid dynamics on detection performance, encouraging the development of more accurate and system-specific detection strategies. A comparative evaluation supported by standardized criteria further facilitates the development of adaptive, robust, and standards-compliant IDM strategies that enhance overall grid stability, detection accuracy, and operational resilience.

INDEX TERMS Islanding detection methods; Non-detection zone; Distributed generation; Grid-connected inverter

I. INTRODUCTION

Conventional electrical power generation systems are passive systems where the energy is produced at the distribution upstream level and supplied to the customers. However, conventional generation systems have their own disadvantages since they could emit harmful gases, pollute the air, and exhaust natural resources. Therefore, these systems have always been a concern over the years, which has driven the development of distributed generation (DG) by taking the benefits offered by small-scale local renewable energy generation. Typically, the scale of these resources ranges below a few megawatts (MW), and can include photovoltaics, micro hydro turbines, wind turbines, and other types of generators that are powered by geothermal energy or biomass.

The introduction of these novel generation sources has provided a wider range of energy generation options, among which PV energy stands out as a highly promising and rapidly advancing technology.

However, new challenges have also emerged related to the islanding detection, system protection, operation, reliability, control, and power quality within the electrical power system [1-4]. Among these issues, unintentional islanding represents the most critical problem for DGs and PV generators. Islanding can happen when a DG network is intentionally or unintentionally disconnected, leading to an isolated operation. When a disconnection occurs between the network and the distribution grid, due to a fault in the system, an unintended island emerges.

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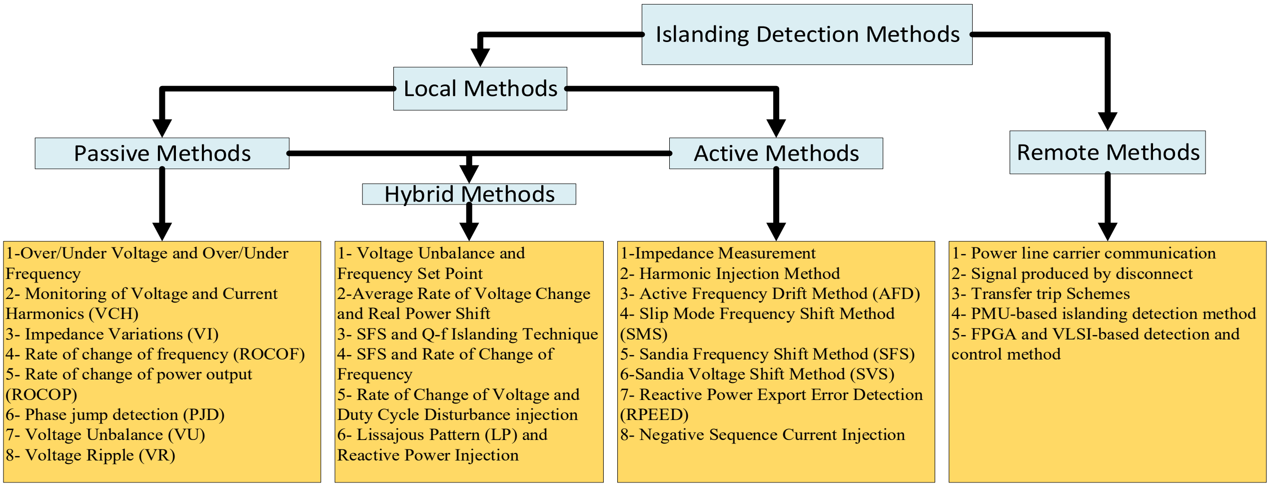

Figure 1: Islanding detection methods classification

So far, various techniques have been developed to address this issue [5-7]. Many research efforts have been focused on investigating different methods for detecting islanding [5, 7-23]. These methods can be categorized into two main groups: (1) local methods, which includes passive and active approaches, and their combinations named hybrid methods, and (2) communication–based methods, which are also named remote techniques.

Among the local methods, passive islanding detection methods were first developed that rely on the observation of changes in the parameters of the system to identify the occurrence of islanding [24, 25]. These methods continuously monitor different system parameters including current, frequency, voltage, and harmonic to detect and handle islanding based on these parameter changes and the thresholds associated with the parameter changes. In [22], a deep analysis is conducted on how to use passive parameters as islanding detection signatures. This work evaluates the effectiveness of islanding detection schemes in the context of degraded power quality resulting from the rising integration of renewable DGs into the electric grid. An evaluation of passive islanding detection techniques in the direct current (DC) microgrids is presented in [26] by employing rate of change of voltage and rate of change of current for islanding detection.

Conversely, active methods intentionally introduce a disturbance into the grid system to assess its impact on parameters like frequency and voltage, impedance, power [12, 25]. In [27], several active islanding detection techniques have been discussed and compared for utility-connected microgrid systems and a comparative study is done in [28] between passive and active methods.

Hybrid methods combine active and passive approaches to improve islanding detection while minimizing drawbacks. Passive methods monitor system parameters without affecting power quality but have large NDZ. Active methods enhance detection by injecting disturbances but can degrade power quality if used continuously. Hybrid techniques address this by using passive monitoring to detect potential islanding and activating the active approach only when necessary. This ensures reliable detection while maintaining system stability, making hybrid methods ideal for applications like distributed generation and microgrids [7, 25, 29].

Remote methods rely on establishing communication links between DGs and the utility grid [30-35]. In these methods, the communication system is developed based on the detection need on the network side. These methods have minimal or negligible NDZ, ensuring minimal impact on power quality. These methods have proved high efficiency in the systems with multiple inverters. Nevertheless, the implementation of such systems requires a substantial investment, rendering them economically impractical for small-scale local networks [36]. The flowchart in Fig. 1 illustrates a general classification of these methods.

Although numerous islanding detection methods and review studies have been developed over the past decades, islanding events continue to occur undetected under certain operating conditions, posing risks to system reliability and safety. Many persistent challenges such as the NDZ, false tripping, and sensitivity to grid dynamics remain unresolved. To address these gaps, a structured and critical comparison of existing methods is essential for exposing technical limitations, identifying opportunities for improvement, and deriving insights that can inform the development of more robust and context-aware detection strategies. In this context, various local islanding detection methods have emerged; therefore, this paper provides a comprehensive and in-depth review of passive, active, and hybrid approaches. The work emphasizes both the evaluation of detection principles and the comparative analysis of the performance, highlighting key features, implementation challenges, and unresolved limitations. Specific attention is given to outlining the practical strengths and limitations of each method and their influence on detection performance under typical grid conditions. By

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systematically organizing and analyzing these methods based on their strengths and shortcomings, this review contributes actionable insights to support future research and the development of more effective islanding detection solutions for DG-based systems, especially solar PV systems.

This paper proceeds as follows: Section II explores the standards for islanding detection. In Section III, main islanding detection challenges are introduced and evaluated. In Section IV, a detailed review of various passive islanding detection techniques is presented. Section V offers a detailed analysis of the active islanding detection systems. In Section VI, hybrid methods are discussed. Section VII gives a thorough discussion and comparison evaluation of passive, active, and hybrid islanding detection methods. Finally, a conclusion is given in Section VIII.

II. Islanding Detection Standards for DG Equipped with Photovoltaic Systems

Multiple research studies have indicated that the isolation of DGs can cause damage to the electrical devices and pose risks to the safety of line workers. In order to decrease these dangers, the power industry has developed several Islanding Detection (IDS) standards. This section aim to provide comprehensive safety guidelines for operating grid-feeding, grid-forming, and grid-supporting modes of DGs [37]. These standards have been extensively employed by professionals to guide the development of their products. Some of the commonly adopted ID standards include IEEE 1547 [38, 39], IEC 62116, and IEEE 929 [40, 41]. Table 1 presents a brief overview of these standards [7].

Some of these standards will be discussed in more detail in the following section and attempts are made to explain standard test procedures and their challenges. Fig. 2 shows the test system that is mostly used in islanding detection studies and standards.

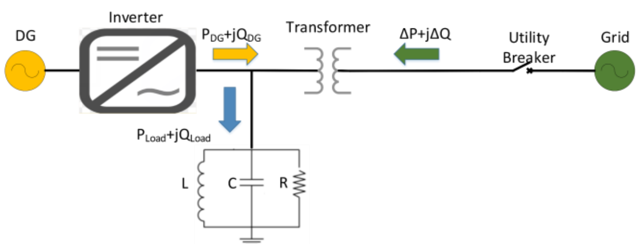

Figure 2: Single line diagram of the test System

In this figure, P_{DG} and Q_{DG} represent the active and reactive power generated by the DG, P_{load} and Q_{load} denote the active and reactive power consumed by the load and ΔP and ΔQ indicate the active and reactive power exchanged with the grid.

A. IEEE Std. 929-2000

IEEE 929-2000 aimed to establish the technical requirements for PV system interconnections, allowing individual utilities to adopt these as a standard. While it covers various topics, its most distinctive section focuses on safety and protection functions, particularly the PV inverter's response to abnormal utility conditions. The IEEE 929-2000 standard was developed to outline the required frequency and voltage parameters for the distribution grid [42]. A key goal of IEEE 929 was to establish a test procedure to verify that an inverter has an effective anti-islanding technique [41]. Currently, a recognized procedure for worst-case testing has been established in the United States to evaluate whether PV inverter controls can sustain a distributed resource islanding scenario. The test involves creating an islanding condition with the under-test inverter using an RLC load, as shown in Fig. 2, whose resonant frequency must be adjusted to match the specific operating frequency of the local power grid, which in the North America is equal to 60 Hz. When the RLC load's resonant frequency closely aligns with the system's nominal frequency, and the DG is operating autonomously at or near the nominal frequency, the frequency may exhibit minimal deviations during islanding. Consequently, relying solely on frequency variations for islanding detection becomes challenging. In addition, this load should be practically matched in terms of real power to closely align with the PV inverter output. This is because most inverter-interfaced distributed generators typically function with a power factor of one to maximize the kilowatt-hour kWh production. Additionally, its Q factor, represented by the quality factor defined in (1), should be less than 2.5. By suggesting a Q-factor less than 2.5, the standard aims to ensure that an islanding detection system is tested under conditions that reflect a practical and sufficiently damped power system, enhancing the safety and reliability of electricity supply. Detailed test procedures for achieving this can be found in [43].

$$Q = tan(arccosine\ [pf]) \tag{1}$$

In (1), pf is the power factor, and since numerous anti-islanding detection techniques are proposed based on the fluctuations in voltage and/or frequency, the electrical system noise level can notably impact the testing outcomes. Furthermore, the utility grid impedance or simulated utility grid can play a role in the test results. Although, a simulated grid can simplify the testing procedure, it is crucial that the simulated voltage waveform conforms to the established standards in terms of harmonics and waveform quality.

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TABLE 1: COMPARISON OF STANDARDS FOR ISLANDING DETECTION

Standards	Permissible voltage limit	Frequency limit	Detection time	Quality Factor (Qf)
UL 1741	$88\%\ of\ v_{nom} < v_{nom} < 110\%\ of\ v_{nom}$	$59.3Hz < f_{nom} < 60.5Hz$	$t < 2\ sec$	2.5
IEEE 1547-2018	$88\%\ of\ v_{nom} < v_{nom} < 110\%\ of\ v_{nom}$	$59.3Hz < f_{nom} < 60.5Hz$	$t < 2\ sec$	1
IEC 62116	$88\%\ of\ v_{nom} < v_{nom} < 110\%\ of\ v_{nom}$	$f_{nom} - 1.5Hz < f_{nom} < f_{nom} + 1.5Hz$	$t < 2\ sec$	1
IEC 929	$88\%\ of\ v_{nom} < v_{nom} < 110\%\ of\ v_{nom}$	$59.3Hz < f_{nom} < 60.5Hz$	$t < 2\ sec$	2.5

This adherence is necessary to guarantee consistent and dependable results. Additionally, the modelled utility grid should precisely emulate the correct impedance of the source at the harmonic and fundamental frequencies that are relevant to the inverter undergoing testing. In addition, experimental evidence indicates that certain inverters exhibit faster responses at lower power levels, while others show quicker reactions at or near their rated power levels. Therefore, it is recommended to conduct testing at different power levels. Given that a comprehensive understanding of all anti-islanding methods and models has not yet been achieved, testing across a range of power levels is essential [43].

B. UL1741

Due to the wide range of islanding detection methods discussed in the literature, regulatory organizations such as Underwriters Laboratories Inc. (UL) have included an anti-islanding test in their respective standards to standardize detection criteria. The tests outlined in UL and IEEE documents are quite similar. The islanding detection test, which uses a tuned RLC load, is part of the baseline testing protocol for non-islanding PV inverters outlined in the IEEE 929-2000 standard.

This test is also incorporated within the UL Standard 1741 for inverters with a capacity below 10 kW [43]. The UL1741 standard anti-islanding test specifies that any DG unit must stop delivering power within 2 seconds after the breaker is opened, to prevent islanding operation mode. The UL1741 standard for anti-islanding tests requires that any distributed generation (DG) unit must cease power delivery within 2 seconds after breaker is opened to prevent islanding operation [44]. The load in the possible islanding scenario is represented using a parallel RLC circuit, which must be tuned to resonate at 60 Hz ± 0.1 Hz and have a quality factor of less than 1.8. As a result, the load will behave a completely resistive load operating at the standard line frequency of 60 Hz. The value of R must be adjusted to dissipate the converter's output power at a given voltage. This ensures that no fundamental current component flows to or from the utility during steady-state operation if the DG unit is working with a power factor equal to one. This scenario represents the worst case for islanding detection because opening breaker does not lead to a notable shift in either voltage or frequency at the load terminals [45].

C. IEC 62116

The IEC 62116 standard was enacted to establish a test procedure for assessing the islanding prevention effectiveness of PV inverters, regardless of the islanding detection method employed. IEC62116 also employs a worst-case islanded circuit scenario. Fig. 3 depicts the suggested test setup for performing the anti-islanding test according to this standard. The power conditioner is generally connected to a pair of power sources: it receives a direct current from a PV array, and an Alternating Current (AC) either from the main electrical grid or from an independent AC generator. During the test configuration, the AC power supply should be calibrated so that both its voltage and frequency correspond to the standard operating parameters. In addition, the DC input must be set to ensure the power conditioner delivers its usual maximum power, akin to what a fully active PV array would supply.

The same drawbacks outlined in the previous section are relevant to this testing approach. It should be noted that the implementation techniques of an anti-islanding method can influence its NDZ. While the techniques discussed may seem simple, errors in implementation can lead to the creation of an NDZ [43]. For instance, since numerous anti-islanding detection techniques rely on detecting voltage and/or frequency fluctuations, the amount of noise affecting the electrical and measurement circuits can greatly influence the outcomes of tests. The impedance presented by the utility grid, or a utility simulator, may also impact the outcomes of the testing.

D. IEEE 1547-2018

IEEE Standard 1547-2018 offers guidelines for connecting a Distributed Energy Resource (DER) to the utility Electric Power System (EPS), also referred to as the primary AC grid. This standard mandates that the DER control system possesses adequate response time to ensure that other DERs and loads remain unaffected by transients when transitioning from grid-connected mode to intentional islanding mode [46]. Per IEEE Std 1547-2018, DERs must identify and discontinue energizing the area EPS within 2 seconds of island formation. For the majority of residential and commercial DERs, this mandate is embedded by manufacturers during fabrication. Moreover, the DERs' ability to comply with this standard is meticulously tested prior to being deployed in the field. IEEE Std 1547-2018 mandates that DERs sustain anti-islanding capabilities both with and without grid support functions activated. Conversely, anti-islanding features

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should not obstruct grid support functions or the new voltage and frequency ride-through criteria for all DERs [47]. It also stipulates that a DER remains connected for a designated period, referred to as voltage ride-through time, during permissible voltage disturbances in the utility EPS voltage [48]. It should be noted that the voltage and frequency deviations for IEEE 1547 and IEEE 929 are identical for safe operation. The voltage range is 0.88–1.10 of the nominal voltage, and the frequency range is between 59.3–60.5 Hz for both IEEE 1547 and IEEE 929 [49].

III. Islanding Detection Challenges

So far, various approaches have been proposed for the detection of islanding conditions. Despite these efforts, the system has remained at the risk of experiencing islanding, as reports indicate the occurrence of such events. Indeed, the primary challenge in islanding detection lies in selecting the right monitoring parameters that are both effective and robust in identifying islanding conditions.

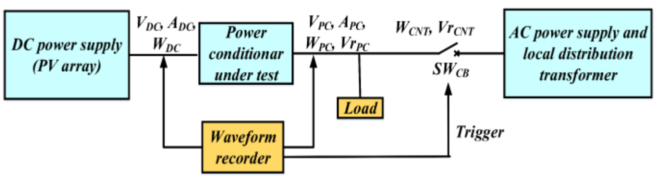

Figure 3: Suggested test setup for performing the anti-islanding test according to IEC 62116 Standard

Additionally, determining the appropriate threshold for these parameters becomes crucial as they should consider the overall disturbances present in the system. This careful consideration helps in avoiding false tripping, where the detection system mistakenly triggers protective actions when islanding is not actually occurring. In order to effectively detect islanding events, it is crucial to have a detailed understanding of how the system operates, controls, the system components, and their interactions. This helps in developing accurate models that can be used to analyze and identify abnormal conditions associated with islanding. Specially, to implement a successful passive islanding detection technique, a thorough comprehension of the system's modeling and its challenges are necessary. Therefore, in this section, the main challenges of the system are discussed, and attempts are made to highlight their significance within the system's framework.

A. THRESHOLD

The key distinction between grid-connected mode and islanding mode lies in the setting of threshold values. When these thresholds for acceptable disturbances are set too low, it can result in nuisance tripping, that would cause unwarranted interruptions to observe. Conversely, if the thresholds are set too high, the protective devices may not respond to the islanding conditions, potentially jeopardizing safety. Striking the right balance is crucial to ensure a reliable and secure operation between the two modes. The merits of passive islanding detection methods are fast response and the absence of system disturbances. However, methods that rely on parameters exceeding the threshold due to power mismatch face difficulties in eliminating NDZ and the detection speed of these methods is influenced by power mismatch that make it difficult to predict. In addition, the efforts to increase different performance indices encounter several intricate challenges that could impose some limitations on one another. For instance, decreasing the threshold of the normal range can increase the detection speed. However, this can lead to a higher likelihood of detection parameters exceeding the threshold during load switching or system transients. Therefore, the error detection ratio may increase. On the other side, by increasing the threshold range, the system NDZ would become larger and may increase the detection time. Therefore, there is always a close relationship between the NDZ reduction and threshold in these systems.

B. Non-Detection Zone (NDZ)

The efficiency of islanding detection methods is typically measured by the NDZ. The NDZ refers to the range of power variation (measured by the difference between the DG and the load) wherein a testing islanding detection scheme fails to recognize this particular condition [50, 51]. This zone's size is primarily influenced by the local load levels connected to the DG. As the active power consumed by these loads approaches the active power supplied by the DG, the likelihood of islanding formation increases. Likewise, when the resonant frequency of the local load gets closer to the nominal frequency of the local grid, the likelihood of an islanding event occurring also increases [52]. The load type mostly employed in islanding detection tests is a parallel RLC circuit model. This specific circuit would present a primary challenge to the electric utility in islanding analysis due to its tendency to create more challenging conditions for detecting islanding through existing techniques. Typically, detection methods for islanding should be adapted to handling nonlinear loads generating current harmonics or those with constant power consumption.

The existence of non-detection zones is the main problem of islanding detection methods. NDZ of passive detection methods relies on monitoring voltage, phase deviation and frequency. However, NDZ of active methods have been described based on the load parameters. This implies that the effectiveness of active methods in detecting islanding can vary based on how the load within the islanded system responds to the introduced disturbances. If the load characteristics mask the disturbance or if the system responds in a way that mimics normal operation, the active method may fail to detect the islanding condition. As discussed earlier, when the amount of the power demand and power generation are close together,

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passive islanding detection methods will suffer a large NDZ. On the other hand, passive methods have been demonstrated an acceptable effectiveness if the power imbalance between the generation and load becomes noticeable. The power imbalance often arises during the shift between islanded and grid-connected modes, or vice versa, especially when DERs supply electricity to the main grid just before the transition [53, 54].

Currently, there exists two types of NDZ representation methods: the Power Mismatch Space Representation (PMSR) and the Load Parameter Space Representation (LPSR) [52]. In PMSR, the active power flow and reactive power flow to the grid are utilized. Upon islanding, the voltage and frequency of the islanding system shift to a new operating point. This ensures a balanced power equation between the PV generation and the local load consumption.

The following equations show the imbalance of active and reactive powers between the load and DG at the point of common coupling (PCC) point.

$$\Delta P = P_{Load} - P_{pv} \tag{1}$$

$$\Delta Q = Q_{Load} - Q_{pv} \tag{2}$$

Therefore, NDZ of active power can be derived from the following equation:

$$\left(\frac{v}{v_{max}}\right)^2 - 1 \leq \frac{\Delta P}{P} \leq \left(\frac{v}{v_{min}}\right)^2 - 1 \tag{3}$$

And NDZ of reactive power can be defined as:

$$Q_f\left(1 - \left(\frac{f}{f_{min}}\right)^2\right) \leq \frac{\Delta Q}{Q} \leq Q_f\left(1 - \left(\frac{f}{f_{max}}\right)^2\right) \tag{4}$$

In this equation, the quality factor Q_f plays a pivotal role as a critical parameter in determining islanding test conditions. In addition, $V_{\max}$, $V_{\min}$, $f_{\max}$, $f_{\min}$ are the respective thresholds for over/under voltage and over/under frequency. Equations (3) and (4) indicate that when the mismatch in active and reactive power remains within defined limits determined by the voltage and frequency thresholds the resulting voltage and frequency will stay within their nominal ranges even after grid disconnection. Consequently, an islanded condition may occur and persist undetected.

However, PMSR is not sufficient for evaluating the effectiveness of conventional anti-islanding methods due to the potential for various combinations of reactive power mismatches between L (inductance) and C (capacitance). Among these combinations, some may trigger islanding while others may not [55].

In the case of the Load Phase Shift Relation (LPSR), the phase criterion is used to characterize the NDZ. This criterion states that the sum of the load phase angle and the inverter phase angle should equal zero. Under such conditions, the voltage and frequency at the PCC may remain within acceptable ranges even after grid disconnection, allowing an islanding condition to persist undetected. The load phase angle depicted in the next equation, and expressed as a function of frequency and the RLC parameters, provides insight into the specific operating points where islanding detection becomes challenging [52]:

$$Load\ Phase = -tan^{-1}[R\left(2\pi fC - \frac{1}{2\pi fL}\right)] \tag{5}$$

Where the load phase angle is calculated based on the frequency-dependent impedance of the RLC load. 2πfC and 1/(2πfL) represent the capacitive and inductive reactances, respectively.

Generally, NDZ could have different shapes depending on the type and structure of the distribution system. In addition, for inverter-based structures, the control strategy plays a significant role. In fact, the control method is effective on the active and reactive power mismatch at the PCC point [51].

C. Load Parameter Space (LPS)

The Load Parameter Space (LPS) plays a vital role in islanding detection since it serves as the foundation for recognizing variations and serves as a point of comparison for the system's performance in regular grid-connected operations versus a potential islanding scenario. In fact, by analyzing and monitoring the parameter changes in the LPS, different algorithms and methods can detect anomalies that could indicate the occurrence of islanding.

The relationship between LPS and NDZ concepts is essential for determining the effectiveness of islanding detection methods. If the normal operating conditions (as defined by the load parameter space) overlap significantly with the conditions that characterize the NDZ, detecting islanding becomes more challenging. In other words, when the parameters during normal operation and an islanding event are similar, the system may fail to distinguish between these states, placing them within the NDZ. Understanding this relationship is key to optimizing the parameters of detection systems to minimize the NDZ. By fine-tuning the detection thresholds or criteria according to the typical load parameter space, engineers can decrease the chances of misclassifying normal operating conditions as islanding.

The efficiency of a passive islanding detection technique is evaluated by using the NDZ of the method in $\Delta P \times \Delta Q$ space. Although, some methods like Active Frequency Drifting IDMs have represented an improved performance metrics in terms of islanding detection, their NDZ cannot be defined in $\Delta P \times \Delta Q$ space. Therefore, the

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NDZ of these methods would be a challenge and attempts should be made to define suitable parameter space to overcome this problem. A load parameter space is developed based on the quality factor and resonant frequency of the local load (Q_f versus f_0) [56]. It uses a curve to depict the NDZ of frequency drifting for various RLC loads. In this method, for a given set of L and C elements, an increase in R means an increase in Q_f. Here, it is mentioned that $\Delta P \times \Delta Q$ space is not useful because, although various RLC loads could have various NDZ for islanding detection, the NDZ would be represented at the same zone [56]. This means that different configurations of RLC loads, which might have unique responses to islanding conditions, could appear identical in the ΔP × ΔQ space. Such a representation fails to capture the nuanced differences in how each RLC load configuration might affect the islanding detection capability. Therefore, it can be concluded that their NDZs are not easily defined within the traditional ΔP × ΔQ space, presenting challenges in assessing their efficiency using this model.

D. Detection time

Ensuring the accuracy and reliability of the detection system is crucial. The time it takes for the system to identify an islanding event is known as detection time. In fact, the detection time refers to the period starting from when a microgrid disconnects from the main grid until the islanding is successfully detected by islanding detection methods, which is defined as:

$$\Delta T = T_{IDM} - T_{Trip} \tag{6}$$

where ΔT is the run-on time, T_{IDM} is the time at which islanding detection occurs, T_{Trip} is the time at which DG disconnects from the grid. A smaller ΔT indicates faster and more effective islanding detection performance, which is critical for ensuring system safety and compliance with grid interconnection standards such as IEEE 1547. As mentioned, according to IEEE 1547, islanding detection must occur within 2 seconds. However, it is important to emphasize that the IDM should be evaluated across a range of islanding scenarios and operating conditions to accurately assess its detection time.

E. FALSE DETECTION RATIO

Islanding detection techniques must remain reliable and avoid false triggering under non-islanding conditions [57, 58]. To assess this aspect of performance, the False Detection Ratio (FDR) is introduced and calculated using the following expression.

$$FDR = \frac{N_F}{N_T} \times 100 \tag{7}$$

Where N_T represents the total number of scenarios evaluated both islanding and non-islanding and N_F denotes the count of incorrect detection events. Therefore, the following conditions must be taken into account when assessing the performance of the IDM:

- The effectiveness of the islanding detection methods IDMs may be compromised under weak grid conditions, typically marked by high line impedance and low short-circuit capacity. These conditions cause rapid variations in system parameters, which can result in transient behaviors that may lead to incorrect operation or false triggering of IDMs [59].
- Load and capacitor switching events can induce significant oscillations in frequency, voltage, power, and other system parameters, potentially leading to false triggering. Consequently, it is essential to assess the performance of islanding detection methods (IDMs) under conditions involving the highest expected levels of load or capacitor switching. [59].
- The startup of large induction motors particularly through direct-on-line methods can cause a significant increase in reactive power demand and a noticeable voltage drop within small-scale grid-connected microgrids. These transient conditions may lead to incorrect operation or false triggering of IDMs [59, 60].
- Due to the fault ride-through (FRT) requirements in modern power systems, most distributed generation (DG) units are expected to remain connected during fault events. Consequently, IDMs must operate reliably and avoid false detection during such conditions [59]. In contrast, fault-initiated islanding may occur when an upstream fault causes protective devices to disconnect the DG at the point of common coupling (PCC), isolating it from the grid. In these scenarios, the IDM must promptly and accurately identify the transition to islanded operation [61].

F. Low-Voltage Ride-Through (LVRT)

One of the key challenges in islanding detection arises from the need to comply with LVRT requirements mandated by standards such as IEEE 1547-2018. As mentioned earlier, IEEE 1547-2018 Specifies that unintentional islanding must be detected within 2 seconds [33]. However, it is also mentioned that ride-through performance requires DGs to ride through voltage and frequency excursions within defined limits and not trip unless thresholds are violated persistently. A severe grid outage may result if grid-connected PV inverters lack an effective FRT capability [62].

These requirements prevent distributed generators from disconnecting during temporary voltage sags, which directly conflicts with traditional islanding detection methods that rely on abnormal voltage or frequency deviations as indicators of islanding. Therefore, the inverter is required to ride through voltage disturbances, the detection threshold must be wider which increases the NDZ. This means that islanding conditions can persist undetected for longer, especially under

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load-generation matching or weak grid conditions. As a result, the effectiveness of passive methods is reduced, and the reliability of detection during LVRT events becomes compromised. Hence, passive techniques suffer from increased NDZ due to voltage sags being tolerated under LVRT, making them unreliable for fast islanding detection. This necessitates the development of advanced or hybrid detection techniques that can operate within LVRT constraints without causing false trips or delays.

Some active techniques (e.g., phase or frequency perturbation) might be restricted or delayed during LVRT to avoid destabilizing the system, limiting their effectiveness when fast detection is needed. On the other hand, faults and disturbances within the distribution or sub-transmission system can cause fluctuations in voltage and frequency, which may interfere with the correct operation of anti-islanding protection mechanisms. This can lead to the unintended disconnection of DG units, resulting in economic losses and diminished performance of the Bulk Power System [63].

Islanding detection algorithms must balance sensitivity for fast detection with grid-code compliance to avoid false trips during LVRT. Numerous research efforts have focused on achieving coordinated operation between LVRT functionality and anti-islanding protection. While several proposed solutions are reviewed in this work, the fundamental conflict between maintaining LVRT compliance and ensuring effective islanding detection persists. This ongoing challenge highlights the need for more sophisticated or integrated detection approaches. An integrated control algorithm is developed in [64] for islanding detection and LVRT in a two-stage PV inverter. Islanding is detected via current saturation in the voltage control loop, independent of grid voltage disturbances. The method ensures detection within 2 seconds, meeting IEEE 1547 standards. LVRT is implemented using an inequality condition on the integrated d-axis voltage, enabling accurate detection regardless of sag type. A method was proposed in [65] for a grid-connected photovoltaic (GCPV) inverter that supports LVRT, provides reactive power compensation, and incorporates islanding detection capabilities. In another work, a passive multicriteria-based islanding detection method has been proposed, which integrates voltage unbalance, harmonic distortion, and fault verification logic so that islanding can be detected quickly and reliably even under power-balanced conditions. The method is designed to comply with LVRT requirements, ensuring that distributed generators remain connected during grid disturbances while still meeting the disconnection criteria of IEEE 1547-2018 [66].

Protection devices play a critical role in maintaining system stability and safety during grid disturbances; however, their coordination becomes increasingly complex under LVRT conditions. A fault current limitation approach utilizing a Current Limiting Device (CLD) has been proposed to enhance protection coordination and reduce the risk of unintentional islanding in GCPV systems. By limiting fault current magnitudes, the CLD helps maintain system connectivity during voltage disturbances, prevents premature disconnection of distributed generation units, and ensures compliance with LVRT requirements [67-69]. The protection relay configurations must align with both ride-through and anti-islanding standards to enhance overall protection reliability. Accordingly, another study examines passive anti-islanding protection mechanisms tailored to comply with ride-through criteria under typical electrical system disturbances [70]. This study assessed the performance of passive anti-islanding protection functions in conjunction with ride-through requirements under both islanding and non-islanding grid disturbances. The findings indicated that the updated threshold values did not compromise the effectiveness of anti-islanding protection during the analyzed islanding scenarios except in cases where the voltage balance function was not correctly configured. The method in [71] addresses the future need for ancillary services in low-voltage grids by proposing a method that enables simultaneous LVRT capability and anti-islanding protection in three-phase inverters. The approach relies on constant voltage and frequency monitoring, allowing the inverter to respond appropriately to varying grid conditions. It ensures system stability while preventing unintentional islanding, even under low-voltage scenarios. Notably, the implementation of LVRT is shown to enhance islanding detection rather than interfere with it.

G. MPPT Interaction with Islanding Detection Techniques

Tracking the maximum power point (MPP) of a PV array is a fundamental aspect of PV system operation. Over the years, numerous techniques have been proposed and implemented for this purpose [72-76]. Under normal grid-connected conditions, MPPT algorithms continuously adjust the voltage and current operating points of the PV array to maximize power extraction based on environmental conditions. However, their behavior in islanded operation poses significant challenges for islanding detection algorithms, especially in systems employing passive and active detection methods [77]. Various techniques have been developed to enable GCPV inverters to perform MPPT and ensure anti-islanding protection [78-80]. However, one significant challenge lies in the limited disclosure by manufacturers regarding the specific algorithms integrated into their devices, making it difficult to assess and compare their effectiveness across different applications [78].

Another key challenge arises from the fact that during islanded operation, MPPT algorithms may continue to adjust the PV output to match the local load, unintentionally masking the power imbalance that some islanding detection methods rely on [81]. For instance, one challenge in active islanding detection methods is the mismatch between the fast dynamic response of the current control loop and the slower operation of the MPPT algorithm. Since MPPT operates at a lower frequency, disturbances injected through the voltage control

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loop may not induce sufficient deviation in local variables to trigger reliable detection. This limitation can reduce the effectiveness of islanding detection, particularly when relying on voltage-based perturbations. As a result, most active and hybrid techniques inject periodic disturbances through the current control loop, which enables faster destabilization of key system parameters and enhances detection reliability without significantly interfering with MPPT performance [82].

Another significant challenge of passive islanding detection methods is their reliance on detecting disturbances caused by imbalances in active and reactive power. However, during normal operation, the MPPT algorithm continuously adapts the power output of distributed generation units to match load variations. This dynamic adjustment smooths out the very fluctuations passive methods depend on, thereby diminishing their sensitivity to islanding events. As a result, the non-detection zone (NDZ) is enlarged, increasing the risk that islanded conditions may persist undetected. Exploring solutions such as adaptive MPPT control or temporary suspension mechanisms could help reduce this vulnerability and enhance detection reliability.

On the other hand, islanding detection methods applied in systems equipped with MPPT may adversely affect the proper functioning of the MPPT algorithm. This interaction poses a significant challenge that has been acknowledged in recent research [83]. To address this issue, various strategies have been proposed, particularly those that consider the nature and characteristics of the injected disturbance. For instance, the active method proposed in [83], adjusts the current reference such that it is elevated by K% above the nominal value during the first line cycle, and subsequently reduced by K% below the nominal value in the following line cycle. This alternating pattern ensures that the average real power output from the PV system remains constant over the two consecutive line cycles, thereby preserving the functionality of the inverter's algorithm. Some active islanding detection methods, function by injecting deliberate voltage or frequency perturbations to provoke identifiable system responses under islanded conditions [5, 13, 84, 85]. However, these injected signals can disrupt the operation of MPPT algorithms, which rely on stable voltage and current measurements to optimize energy extraction from PV systems. Such perturbations particularly when introduced during normal grid-connected operation can be misinterpreted by MPPT techniques, resulting in tracking errors, energy losses, and even inverter instability in weak grid scenarios [77]. Therefore, a key trade-off in PV systems lies between preserving MPPT accuracy, energy efficiency and IDM performance and response time. High MPPT accuracy maximizes energy harvest but can mask power imbalances, delaying passive IDM response and expanding the NDZ. Conversely, active IDMs inject perturbations to speed up detection, but these can interfere with MPPT algorithms, reducing tracking efficiency and system stability.

To mitigate these issues, researchers have proposed coordinated control strategies and hybrid detection methods that account for MPPT dynamics [77, 79]. Additionally, advanced coordinated control frameworks, such as Finite Control Set Model (FCSM) Predictive Control have been explored to balance accurate islanding detection with efficient MPPT performance, particularly under dynamically changing grid conditions [5]. Although some research has addressed the challenges between islanding detection and MPPT, further studies are still essential to advance understanding in this area. Future work may benefit from the development of adaptive MPPT strategies, detection-aware control algorithms, or machine learning techniques capable of distinguishing between MPPT behavior and islanding events, ultimately improving both detection reliability and energy optimization.

In addition, to mitigate the adverse interaction between MPPT operation and islanding detection methods, dual-loop control architectures or supervisory logic have been proposed [86, 87]. These approaches coordinate MPPT and IDM layers to maintain tracking performance while ensuring reliable detection. Dual-loop control or supervisory logic refers to a coordinated control strategy in which MPPT and islanding detection methods (IDMs) operate as layered or interacting loops typically with MPPT handling fast energy optimization and a higher-level supervisory layer monitoring grid conditions and enabling or adjusting IDM behavior as needed. While this integration can improve overall system performance, it introduces several challenges. Precise coordination is essential to prevent conflicts between MPPT and detection functions; poor timing can delay detection or reduce energy yield. Balancing detection sensitivity with tracking efficiency is a core trade-off, as favoring one often compromises the other. Control transitions may also lead to instability, especially under weak grid conditions. Furthermore, implementation requires advanced sensing, logic, and software integration, while external factors like grid disturbances or irradiance fluctuations complicate real-time decision-making. Lastly, detection perturbations may interfere with MPPT accuracy if not carefully managed [86, 87]. In [88] a hybrid islanding detection technique is developed that integrates MPPT control with an islanding detection mechanism. The method involves monitoring the PCC voltage and injecting a transient disturbance into the inverter's reference current to detect islanding events effectively. This coordinated control strategy ensures both optimal power extraction and reliable islanding detection. Additionally, a hierarchical control structure for DC microgrids is presented in [89]. Their approach includes multiple control layers, where the primary layer handles fast dynamics like MPPT, and higher layers manage supervisory functions, including islanding detection and mode transitions. This layered control ensures stable operation and efficient energy management in microgrids.

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IV. PASSIVE islanding detection techniques

In passive IDMs, the relay situated at the PCC or DG end constantly tracks the fluctuations in measurable system parameters like voltage, current, and frequency. In instances of islanding or faults, these power signal parameters undergo notable variations. The principles governing islanding detection in passive methods stem from observing and analyzing these parameter variations, allowing for the formulation of effective detection techniques. A general layout for passive islanding detection technique is depicted in Fig 4. Some common passive islanding detection methods are discussed in the following subsections.

A. Over/under voltage and over/under frequency

This method is developed based on defining a permissible range for voltage and frequency. Therefore, the inverter protection system will trip if either parameter exceeds the specified thresholds. These are considered basic passive islanding detection methods that monitor voltage and frequency at PCC. It should be mentioned that here again power mismatch plays a significant role. The frequency or voltage deviation is essential because of the power mismatch. During the islanding condition, voltage and frequency will deviate to satisfy the reactive and active power balance. As expected, this method suffers a large NDZ, and the detection speed depends on the amount of power mismatch between the DG and load. So, it is more appropriate to be used in the systems with more power imbalances.

In [43, 90, 91], the effectiveness of NDZ is analyzed in $\Delta P \times \Delta Q$ space. This study examines a local RLC load while the inverter functions under current control mode, maintaining a unity power factor. Under these circumstances, once islanding occurs, the inverter is responsible for supplying the required power to the load. Therefore, the voltage and frequency values would be changed based on equations (8) and (9):

$$Q_{load} = Q_{Pv} = 0 \quad If \;\; f = f_0 \tag{8}$$

$$P_{load} = P_{Pv} \; and \;\; V_{load} = \begin{cases} \sqrt{P_{pv} R} \\ I_{pv} R \end{cases} \tag{9}$$

where the resonant frequency of the load is denoted as f_0. Q_{load} is the load reactive power, P_{pv} is the active power that is produced by PV and Q_{Pv} is the PV reactive power. P_{load} and V_{load} are the load power and voltage, respectively. These relationships capture the dynamic coupling between voltage, frequency, and power under islanded conditions. Such modeling is essential for accurately assessing NDZ boundaries and understanding how inverter control strategies influence detection performance, especially in weak grid scenarios or during load transients.

When the voltage and current measured at the PCC adhere to the constraints set by the following equations, the islanding event cannot be identified using over/under voltage or over/under frequency detection methods [92].

$$V_{min} \leq V_A \leq V_{max} \tag{10}$$

$$f_{min} \leq f_a \leq f_{max} \tag{11}$$

In these equations, v_{min} and v_{max} define the lower and upper limits of the load voltage range. V_A and f_a are the voltage and frequency of the load, respectively. Additionally, f_{min} and f_{max} correspond to the minimum and maximum frequency thresholds.

In general, traditional over/under voltage and over/under frequency methods are associated with a large NDZ, as they can tolerate substantial active and reactive power mismatches up to 29% and 6%, respectively without triggering detection. This limitation arises from their standard threshold settings, which permit voltage and frequency variations to remain within acceptable bounds even in the presence of islanding [93].

B. Monitoring of Voltage and Current Harmonics (VCH)

Harmonic signature-based methods identify islanding conditions by monitoring variations in harmonic content, which differ across harmonic orders depending on whether the system is grid-connected or operating in islanded mode.

This method relies on observing the Total Harmonic Distortion (THD) and the main system harmonics at the PCC [94]. If the measured values go beyond the predefined limits, the inverter will detect the islanding condition. During normal network performance, the voltage at the PCC is the same as the grid voltage and the THD is almost equal to zero. One key advantage of this method is its consistent effectiveness, even when multiple DGs are connected in parallel at the same PCC. Additionally, it is straightforward to implement. Harmonics generated by each DG will sum up at the PCC. Since THD is a measure that includes all harmonic contents in the system, it does not matter how many sources contribute to it; the THD value at the PCC will be the total distortion caused by all sources. In terms of the limitations, it should be noted that as this technique is derived from analyzing the harmonics present in the voltage and current waveforms. Therefore, its performance also relies on the inverter side of the system. In cases where the PV itself, due to non-linear loads, injects harmonics into the system, it would be difficult to distinguish between the normal and islanding conditions. These complexities can affect harmonic signatures, making it challenging to establish consistent detection thresholds. False detection is the other issue that could reduce the efficiency of this technique. This method generally is susceptible to false detections where normal variations or disturbances in the power system can trigger false alarms. Undesirable temporary

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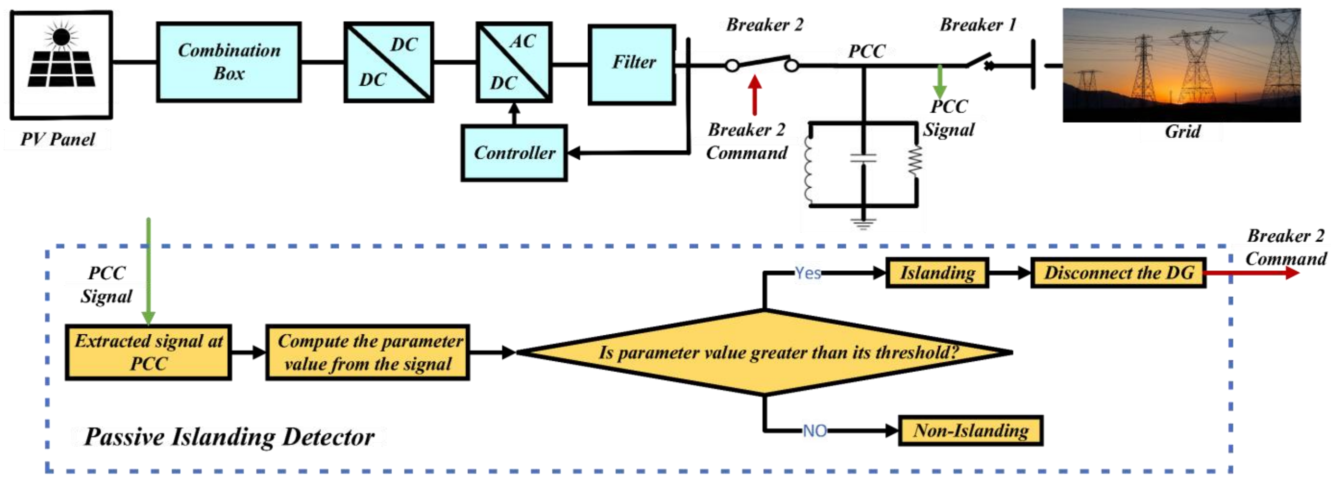

Figure 4: Passive islanding detection technique layout for PV system [95]

harmonic content can be produced due to different system operations such as load switching or system transients that lead to false detections. It is necessary to develop advanced signal processing techniques that can distinguish between disturbances and true islanding conditions to improve the reliability of the method.

In [96], a passive islanding detection method is proposed, which is based on tracking changes in the magnitude of the 5th harmonic voltage at the transition between grid-connected and islanded operation. This approach identifies islanding by analyzing fluctuations in harmonic voltage content at the PCC before and after the primary disconnection event.

The THD associated with voltage and current imbalances at the DG's output terminal are employed in [97] as novel parameters for monitoring power islanding occurrences. However, this approach poses challenges due to the complex detection involving a high Q factor and the threshold selection problem [98, 99].

The study in [100] explores the potential of using voltage harmonics for islanding detection as a cost-effective and straightforward solution for protecting grid-connected PV systems

An advanced passive harmonic signature-based islanding detection method is designed in [101] for fast and reliable performance. The method offers key features such as quick adaptation to grid changes, efficient harmonic signature extraction with low computational demand, high detection accuracy, and strong resilience to external disturbances and interferences. The approach is validated through laboratory experiments, demonstrating its ability to accurately detect islanding even in challenging scenarios involving interference from closely coupled inverters where conventional passive and active methods fail.

C. Impedance Variations (IV)

This technique detects the islanding by measuring the output impedance of the inverter. If DG becomes disconnected from the main grid due to the occurrence of islanding, the inverter output impedance will be changed, and it can be used as an islanding signature. Under normal conditions, the effect on the overall system impedance is minimized due to the dominant low impedance of the main grid. However, when an unbalanced load occurs or when the DGs become isolated from main the grid, the monitoring of impedance at the PCC becomes important. Therefore, if a notable change in impedance is identified, the potential of islanding increases [7]. In [102], islanding detection is carried out by analyzing the magnitude differences between the reference impedance and the measured impedance within a specified frequency range. A sequential impedance-based method is proposed in [103] for islanding detection with zero NDZ. It replaces abrupt impedance changes with the inverter's sequential impedance at the PCC. Islanding is detected when this value exceeds a set threshold.

However, this method has some drawbacks. As the number of connected inverters increases, the effectiveness of this method may decline [5]. Here also, the impedance threshold will be a concern and needs to be set to detect islanding appropriately and avoid false tripping [104]. Load variations could significantly impact the impedance of the system, and can lead to distinct harmonic currents within the network due to alterations in both the quantity and arrangement of the loads [97]. Changes in load characteristics, such as power factor variations or load shedding, can cause fluctuations in the impedance that affect the performance of impedance-based methods. Developing algorithms that can distinguish between load variations and actual islanding events is a challenge. Non-linear loads such as variable-speed drives, can introduce harmonic components and distort the impedance of the power system. These distortions pose

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challenges in accurately measuring and characterizing the impedance. Therefore, considering the effects of non-linear loads on impedance variations is crucial for reliable detection.

D. Rate of change of Frequency (ROCOF)

When a microgrid disconnects from the main grid due to a power mismatch, the system frequency shifts. Therefore, monitoring ROCOF over several cycles would be possible to detect the islanding condition. Here, again setting an appropriate threshold would be a challenge to avoid false detection and make a suitable decision after the occurring of islanding. This approach offers higher sensitivity than OUV/OUF that lets it detect the islanding condition faster within 24ms. This method also can effectively be employed for systems with large power mismatches. However, it is sensitive to system operations such as load switching and system fluctuations. It can be concluded that systems with minimal fluctuation are well-suited for this method. Therefore, this method could be used for detecting islanding for closely matched active power conditions to reduce the NDZ [51]. The primary challenge with the ROCOF method is its difficulty in detecting islanding when the capacities of the generation and load within the isolated system are nearly matched [59]. It should be added that ROCOF relays typically struggle to identify islanding when the active power imbalance is negligible. This happens because minimal deviation in frequency occurs with reduced active power mismatches [105]. Furthermore, as previously discussed, the sensitivity of ROCOF can be compromised when the MPPT algorithm dynamically adjusts power output in response to load variations. As a result, the detectable signatures of islanding are attenuated, leading to an expansion of the non-detection zone (NDZ) and reducing the reliability of the detection mechanism.

An adaptive ROCOF-based passive islanding detection method is proposed in [106] that dynamically adjusts to different microgrid configurations by leveraging phase-locked loop (PLL) settings. Implemented for both generator-only and hybrid microgrids, the method reliably detects islanding even under zero power mismatch and accurately distinguishes it from non-islanding events such as load switching or motor starting. The approach addresses the NDZ limitations of conventional methods and offers a versatile solution for diverse microgrid environments. However, the most significant challenges arise from the extensive NDZ and the difficulty in selecting appropriate detection thresholds [107]. In other word The limitations of this methods lies in its failure to detect islanding under conditions of low power mismatch or when generation and load are perfectly balanced [108].

E. Rate of change of power output (ROCOP)

The ROCOP method aims to identify rapid changes in power output, which can be indicative of an islanding condition. when a distributed generation source remains connected to the main grid, its power output stays relatively stable and follows the grid's demand or operating conditions. However, during the islanding condition the DG source disconnects from the grid and the output power may fluctuate rapidly due to the sudden change in load and operating conditions [9]. Therefore, the rate of change of power should be continuously monitored to detect significant deviations from the expected power output. Once ROCOP exceeds a predefined threshold, the islanding has been indicated. However, the threshold value needs to be determined accurately to avoid false tripping and to discriminate the load switching and actual islanding events [6]. Consequently, this approach is well-suited for detecting islanding scenarios where there is a substantial power imbalance.

It should be also noted that this method could be used as a complementary method to other islanding detection methods, such as ROCOF can be utilized to improve the precision and reliability of islanding detection. If both parameters exceed their respective predetermined thresholds within a certain range, it provides a stronger indication of an islanding event. This combination enhances the ability to differentiate between normal load switching events and actual islanding that reduces the likelihood of false positives or false negatives in the detection process. However, similar to ROCOF, the effectiveness of ROCOP as an islanding detection metric can be significantly diminished when the MPPT algorithm rapidly compensates for variations in load demand. This dynamic adjustment masks the power imbalances that typically arise during islanding conditions, thereby weakening the observable disturbance signatures. Consequently, the non-detection zone (NDZ) is broadened, reducing the accuracy and responsiveness of ROCOP-based detection strategies.

F. Phase jump detection (PJD)

In normal conditions, when the DG remains connected to the main grid, the output voltage and current should be in phase with each other. However, in the islanding conditions there can be a phase shift between them. A phase lock loop is necessary in the inverter to detect the rising or falling zero crossings of the PCC voltage [109]. Therefore, if a significant phase difference is detected, it would be a signature for islanding detection. The operation of PJD is demonstrated in Fig 5. Its primary strength lies in its ability to remain effective, even when multiple inverters are present [5]. This method can detect phase jump rapidly [110]. Typically, the phase jump detection method operates within a detection time ranging from 10 ms to 20 ms [109].

This method has no impact on the quality of output power and the system transient response. However, the threshold must be defined appropriately to increase the method efficiency and avoid false tripping. When DG meets the local demand, the phase jump cannot be detected appropriately. In addition, the PJD scheme might experience frequent false triggers or nuisance tripping owing to transients that arise during motor startups, particularly when the specified threshold value is set

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too low [43, 111]. Additionally, the scheme proves ineffective when dealing with purely resistive loads, wherein the angular disparity between voltage and current registers is zero [111].

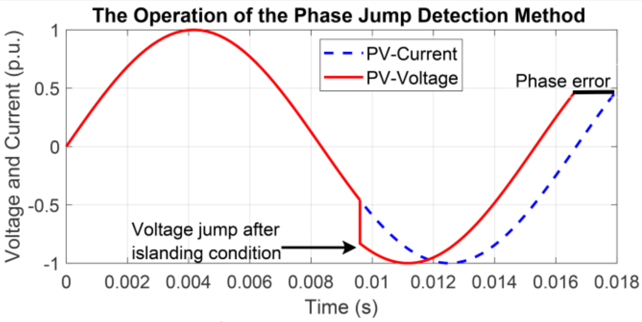

Figure 5: Functionality of the Phase Jump Detection Method [95]

The following equation has been proposed for phase jump algorithm [52, 95, 112]:

$$arctan\left(\frac{\left(\frac{\Delta Q}{Q}\right)}{1+\left(\frac{\Delta P}{P}\right)}\right) \leq \theta_{threshold} \tag{12}$$

The NDZ boundary is defined using an angular condition based on the ratio of reactive to active power mismatches. This formulation effectively maps each operating point in the ΔP–ΔQ space to an angular coordinate, where lower angles indicate a higher risk of non-detection. If the actual phase angle exceeds this $\theta_{threshold}$, it indicates that the current and voltage are out of phase, beyond normal operating conditions, which could be a sign of islanding. In this equation, the correct selection of the $\theta_{threshold}$ is crucial to reduce the method's NDZ and improve the efficiency of the method. As mentioned, certain loads, especially motors, can cause substantial transient phase jumps that can result in false tripping of the PV inverter if the threshold values are set too low.

Compared to other PJD-based methods, in [113], a new passive islanding detection approach for grid-connected PV inverter systems is proposed using wavelet packet transform combined with a back propagation neural network.

G. Voltage Unbalance (VU)

Islanding detection using the voltage imbalance method can be implemented by continuously monitoring the output voltage of the (DG). The method works based on identifying any abrupt deviation or imbalances in the voltage output that could indicate the occurrence of islanding. In a normal grid-connected condition, the voltage across the three phases remains balanced. However, during an islanding event, imbalances can occur in the voltage output. The following equation can be used to define the voltage unbalance at the time t:

$$VU_t = \frac{NS_t}{PS_t} \tag{13}$$

In (13), PS_t and NS_t represent the positive and negative sequence components of the voltage amplitudes, respectively. NS_t, specifically measures the magnitude of the negative sequence voltage at a particular moment in time, and its presence indicates a deviation from perfect balance in the system. In islanding detection, a significant negative sequence component might suggest that the power system is operating in an islanded state.

Furthermore, this method can effectively be employed for systems with small power mismatches because imbalances can be observed even if the load change is small [25, 114, 115]. However, voltage imbalances can occur due to multiple factors such as load changes and network topology variations, and they need to be distinguished with islanding conditions. Therefore, this method requires careful analysis of different system variations to avoid false detections. For instance, the presence of harmonics in the system poses a challenge to accurately extract the negative sequence voltage component, so it makes the calculation of appropriate thresholds complicated [29, 97]. It should be noted that this method exhibits superior suitability for systems where load variations occur frequently, such as capacitor bank switching, or during motor startups, enhancing its applicability in such scenarios [97].

The method introduced in [116] employs a variational mode decomposition technique to extract key modes from measured three-phase voltage signals, using mode singular entropy as an index for islanding detection. This approach is robust against disturbances from normal load variations. However, the presence of system harmonics complicates the extraction of the negative sequence voltage component, making threshold determination challenging. The method is particularly well-suited for systems experiencing frequent load changes, such as during motor startups or capacitor bank switching.

H. Voltage Ripple (VR)

This technique involves tracking, the voltage ripple of the inverter at the PCC and if for a particular duration of time, the voltage ripple of the inverter at the PCC exceeds the predetermined thresholds, then islanding is reported [117, 118]. The technique exhibited no NDZs, and no synchronization is needed for multiple DG sources. The detection time for this method is approximately 210 ms. Here, a delay is required to avoid false tripping because of transient events in the grid connected transient conditions, such as load switching, capacitor switching, and motor, could cause voltage ripple in the system. In addition, distortions and harmonics within the power system can affect voltage ripple characteristics. These additional components can mask or distort the ripple patterns that make it challenging to accurately extract the ripple signal for detection purposes.

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TABLE 2: COMPARATIVE ANALYSIS OF DIFFERENT PASSIVE ISLANDING DETECTION METHODS

IDM Method	NDZ	Detection time	Error detection rate	Advantages	Disadvantages
OUV/OUF [7, 22, 95, 119]	Large	4ms to 2s	High	Simple to implement with low cost with	Unpredictable and varying reaction time
VCH [7, 12, 120]	N/A	45ms	High	The effectiveness does not change when multiple DG units are linked to the same PCC	Thresholds settings and preventing false trips is a significant focal point for this technique
IV [7, 121]	N/A	100ms	High	Suited for interconnected topologies; serves as a base for feature extraction.	Nuisance trip initialization limits this method
ROCOF [12]	Small	24ms	High	Effective method with rapid response	Suitable for small DGs, less reliable with larger ones due to threshold limitations
ROCOP [12, 122]	Smaller than OUV/OUF	24-26ms	High	Suitable for ID with significant power mismatches	Threshold selection issues make the system unreliable
PJD [12]	Large	10-20ms	High	Simple, cost-effective, and no impact on power quality	Complex implementation and difficulty in determining a threshold; unable to detect islanding when distributed generation matches local demand
VU [7, 12, 29]	Large	53ms	None	Effective in detecting unbalances in three-phase systems	It makes the calculation of appropriate thresholds complicated
VR [117]	None	210 ms	High	Not having any NDZ and No synchronization needed for multiple DG sources	Harmonics and power system distortion impact voltage ripple traits

Non-linear loads have been recognized to pose challenges too, especially for voltage ripple techniques [43]. The presence of non-linear loads produces harmonics that may result in false detection of islanding condition [117].

In [123], a method was developed that monitors the time-domain ripple content in the RMS value of the PCC voltage and detects islanding if the ripple exceeds a predefined threshold consistently over a specified duration. This technique remains unaffected by the nominal settings of the DG and is not impacted by the presence of multiple DGs in the system.

The method proposed in [124] involves monitoring the variations in the single-phase voltage waveform at the PCC through a time-domain method to identify and detect islanding conditions. The method does not have any NDZ and is an inexpensive method in comparison with the other frequency domain methods. In addition, no synchronization is needed for multiple DG sources. However, the detection speed relies on the power variation between the loads and the DG system [17].

The method developed in [125] analyzes the voltage signal at PCC by extracting its ripple components through multi-level decomposition using Second Generation Wavelet Transform and Maximum Overlap Discrete Wavelet Transform). It effectively identifies all types of islanding events, including cases with no power imbalance, achieving detection in approximately 0.3 seconds.

The combination of monitoring parameters to identify DG islanding is used in [97], where voltage unbalance, along with the THD of the current, is utilized for islanding detection. The study established the one-cycle average of voltage imbalance and its variation, which underwent evaluation at intervals of every 1/4 cycle.

Although, in situations following the loss of the main source, the load on the DG experiences minimal changes, the variation in voltage unbalance occurs due to alterations in network topology and load distribution. Consistently monitoring the imbalance within the DG’s three-phase voltage output could effectively enable the detection of an islanding operation of the DG. In Table 2, an overview and comparison are made among the described passive islanding detection methods.

V. Active islanding detection techniques

Active islanding detection techniques operate by introducing minor fluctuations or disturbances into the PV inverter's output to identify islanding. These perturbations temporarily adjust the inverter's voltage or frequency output according to the predefined patterns or at specific intervals. This approach facilitates continuous monitoring of the system's responses. If

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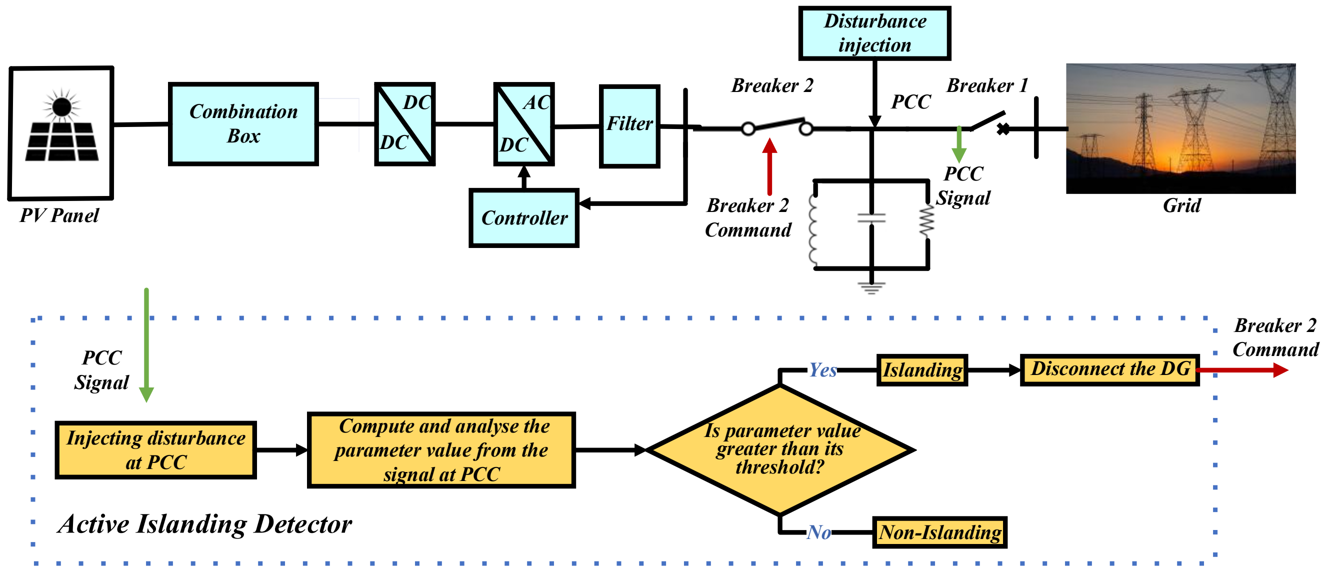

Figure 6: Active islanding detection technique layout for PV system [95]

the PV system operates in an islanded condition; it's reactions to these perturbations differ significantly from its behavior during normal grid-connected operation. Fig. 6 illustrates a basic schematic of the active method layout. In this section, some active methods are evaluated and discussed.

A.Impedance Measurement (IM)

The method is developed based on injecting a small disturbance signal, such as a frequency or voltage deviation, into the system [126]. In [25], a voltage divider is used to introduce a high-frequency signal at the DG terminal. This signal gains increased significance after the grid is no longer connected. Hence, the system response to the injected disturbance should be monitored. This could be done by measuring the resulting change in voltage and current. Therefore, the impedance can be calculated. The primary benefit of this approach is the ability to eliminate the NDZ [127, 128]. The impedance detection method identifies islanding within a timeframe of 0.77 to 0.95 seconds [5].

There are different techniques that can be employed to implement this active method. The technique utilized in [129] involves utilizing a power electronic circuit to introduce a minor current disturbance into the active power network. The measurements of this disturbance current and the resulting transient voltage are then utilized for impedance identification. In [130], the phase angle signal utilized for creating the reference in the current controller undergoes a slight alteration. This modification allows for the estimation of grid impedance by analyzing the grid's response to the generated current. In [24]–[26], both active and reactive power oscillations are harnessed to determine the grid impedance value [131, 132]. An impedance estimation method for islanding detection is proposed in [133], where a small signal from the DG's converter is injected to estimate system impedance. Islanding is identified when the measured impedance exceeds a set threshold. The method improves stability, minimizes false trips, and reliably detects islanding even under perfect power balance.

However, the impedance detection method generally has the following issues: it cannot be used in systems with parallel inverters as each inverter injects a disturbance to the system. In systems with multiple DG units, interactions between reactive power disturbances from different inverters may lead to mutual cancellation or interference. The current approaches utilizing a centralized injection method typically encounter difficulties in interpreting the system's impedance responses. Consequently, this may lead to significant errors when applied in practical scenarios [134]. In addition, active impedance measurement methods often require the integration of detection algorithms with the control system of the inverter. This integration can pose challenges in terms of compatibility, communication protocols, and response times. Coordinating the islanding detection functionality with other control functions within the inverter without impacting its overall performance requires careful design and implementation [95].

B. Harmonic Injection method (HI)

This approach represents a specific instance of the harmonic monitoring method. What distinguishes this method as active rather than passive is the intentional injection of a current harmonic at a specific frequency into the PCC using the PV inverter. The monitoring PLL is specifically designed to identify fluctuations in the harmonic voltage that correspond to the injected harmonic or sub-harmonic currents by the PV inverter [95, 135]. When the grid is active and its impedance at the harmonic frequency is lower than that of the load, the harmonic current primarily flows into the grid, usually without causing any significant voltage disturbances. However, if the grid becomes disconnected, this current is

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likely to be directed toward the load instead. Consequently, the load generates a harmonic voltage that becomes detectable. This method yields an impedance measurement at a precise frequency at the terminals of the inverter.

This method's strength lies in its ability to identify islanding through monitoring PLL synchronized with a particular harmonic, unlike passive harmonic detection methods that require monitoring numerous harmonics. However, its primary drawback is the strong dependence of the harmonic voltage amplitude on the load, potentially leading to a decline in power quality. Additionally, when multiple inverters inject the same harmonics, it can trigger false trips or erroneous detections.

Indeed, grid impedance detection using single harmonic current injection proves to be reliable in a three-phase system with balanced impedance across phases. This method capitalizes on the balance in impedance among the phases for accurate and consistent grid impedance assessment. However, in scenarios where the grid experiences impedance imbalance, the symmetrically injected harmonic current results in an asymmetric harmonic voltage. This asymmetry disrupts the calculation of grid impedances, often leading to inaccuracies and potentially causing failed detection attempts [136].

C. Active Frequency Drift Method (AFD)

This approach introduces minor modifications to the DG's output current waveform. The current waveform is illustrated in Fig 7 and is accompanied by a pure sinusoidal current for the sake of comparison. As illustrated in Fig 7, the output current follows a sinusoidal waveform during the first half-cycle, with a frequency slightly exceeding the nominal value. The difference between the nominal grid frequency and the output current frequency is denoted as Δf. When the current reaches zero, it stays in this state for a duration of t_z (dead time) until the onset of the subsequent half-cycle. In addition, upon reaching zero a second time, it remains in this state for a duration of t_z. The following equation can be used to define the chopping factor [137]:

$$cf = \frac{t_z}{(T_{grid}/2)} \tag{14}$$

where t_z represents the dead time while T_{grid} denotes the period of the grid voltage.

When the utility is connected, the voltage frequency is maintained, however, during islanding, the frequency of the PCC voltage is affected by the inverter current. Consequently, it gradually deviates from the grid frequency until the Over/Under Frequency (OUF) relays detect the islanding condition. Nevertheless, these methods may pose a risk of non-detection, especially when applied to paralleled RLC loads. In addition, in situations involving multiple inverters, it is essential for all inverters to utilize the same AFD implementation. This implies that if one inverter employs an.

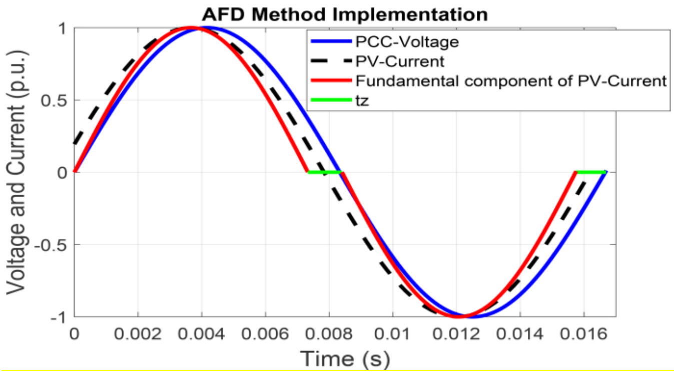

Figure 7: Simulated waveform utilized in the Active Frequency Drift (AFD) method

upward AFD approach, the others should also adopt the same technique If they are configured in exact opposite biases, it would cancel out the intended effect and lead to a failure in detecting islanding conditions.

The effectiveness of the active AFD method is influenced by the initial phase shift between the inverter's output current and the terminal voltage at the moment of utility disconnection. Nevertheless, it continues to function reliably when applied to purely resistive loads. In addition, the AFD technique may increase harmonic distortion within the system and demands careful attention to both detection speed and the size of the NDZ [36]. Despite improvements in reducing the NDZ, the AFD method still causes high harmonic distortion [36, 138]. A novel approach proposed in [36] addresses this by injecting alternative harmonic currents to minimize distortion. Fourier analysis and laboratory tests revealed that the proposed method reduces harmonic distortion by 68% compared to conventional AFD, while achieving a higher chopping factor.

D. Slip mode frequency shift (SMS)

The SMS method operates similarly to the AFD technique, with the key distinction being the manipulation of the phase of the inverter's output voltage. By regulating the inverter's output current and introducing a specific phase offset compared to the common point voltage, this method discerns the presence of an island scenario versus a deviation in the frequency of the common point voltage beyond acceptable levels following a power grid loss. In fact, by making a minor modification to the PLL filter, the method can be employed to detect the islanding.

Fig. 8 presents the block diagram of this approach. SMS alters the phase that leads to a change in the short-term frequency. The technique employs positive feedback to manipulate the PCC voltage phase and, consequently, the short-term frequency. Nevertheless, the method does not have

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any impact on the grid's frequency [99]. Under normal conditions, the DG system functions at a unity power factor, which maintains a zero-phase angle between the PCC voltage and the inverter’s output current. However, in the SMS technique, the phase angle between current and voltage is intentionally modified to facilitate islanding detection. Deviations beyond predetermined thresholds indicate the occurrence of an islanding. In this method, the inverter's current phase angle is determined as follows:

$$\theta_{SMS} = \theta_m sin\left(\frac{\pi}{2}\frac{f^{k-1}-f_n}{f_m-f_n}\right) \tag{15}$$

where θ_m signifies the peak phase angle at frequency f_m, f_n corresponds to the nominal frequency, and f^{k-1} denotes the frequency of the preceding cycle.

For instance, if there is a slight increase in the PCC voltage frequency following a disconnection from the grid, it leads to an elevation in the phase angle of the current. This might lead to a shorter time interval before the next zero crossing of the PCC voltage. The controller interprets this as an uptrend in frequency, thus causing a subsequent increase in the current phase angle. This cycle repeats until the frequency surpasses the limit set by the over-frequency relay. Likewise, in the scenario where the PCC voltage frequency decreases subsequent to a grid disconnection, the frequency continues to decline until it is recognized by the under-frequency relay. Both theoretical analysis and experimental testing have confirmed the effectiveness of this method [139]. Additionally, it demonstrates a better performance as a method for detecting islanding in scenarios involving multiple inverters [95]. In addition, this method is a highly efficient islanding detection method for small NDZs.

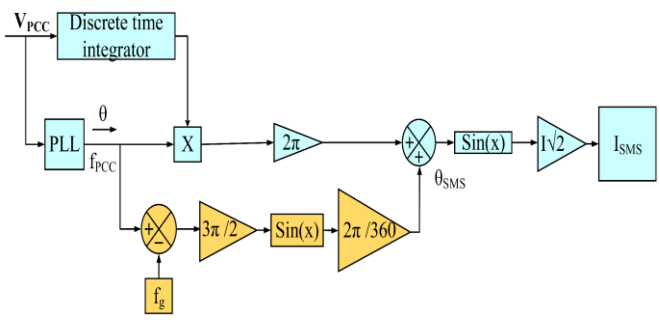

Figure 8: SMS method block diagram [6]

However, the employment of SMS results in a decline in the output power quality of PV inverters. Therefore, this approach not only leads to poor power quality issues at the system level but also presents challenges in transient response [95].

Therefore, determining the appropriate parameters for an islanding detection system is a complex task and has always been a challenge. In [140], a method has been developed to optimize the selection of these parameters, aiming to achieve the most effective and rapid islanding detection while minimizing the adverse effects on power quality and system operation.

In some cases, SMS and AFD methods may fail to detect certain types of islanding events. For instance, if the islanded portion of the grid operates at the same frequency and phase as the main grid, these methods might fail to identify the occurrence of islanding.

In addition, implementing SMS and AFD islanding detection methods can be complex, requiring sophisticated control algorithms as well as complex signal processing methods. This added complexity can raise both the cost and the challenges associated with deployment.

SMS and AFD methods often require accurate knowledge of the system parameters, such as line impedance or load characteristics, for reliable islanding detection. Variations in these parameters can lead to false detections or missed islanding events. A potential limitation in the islanding detection capabilities of AFD and SMS systems becomes highlighted when dealing with paralleled RLC loads due to the relationship between phase angle and operating frequency [141].

In [142], the SMS method was tested for different inverter control algorithms. The analysis shows that this method's efficiency is significantly greater when using a control strategy based on constant current rather than one based on constant power.

E. Sandia frequency shift (SFS) or active frequency drift with positive feedback

This approach represents an expedited variant of the AFD. The SFS improves the performance of the AFD method by adding positive feedback. This adjustment accelerates the deviation of frequency from the standard value and surpasses the rate achieved by the traditional method. As a result, the SFS notably diminishes the NDZ compared to the AFD method. Fig 9 illustrates the block diagram of this approach. In this technique, positive feedback is used to amplify minor fluctuations in frequency. When the DG remains connected to the grid, the grid’s stability prevents significant frequency variations. However, once the grid is disconnected, even small frequency changes can lead to a phase error. If this amount of error exceeds a predefined threshold, the inverter shuts off. Fig. 9 illustrates how the inverter injected current at the PCC can be distorted within a limited duration. Consequently, due to this phenomenon, the inverter's output current will exhibit a slight phase lead with respect to the voltage, which is dependent on the frequency. This leads to the creation of a positive feedback loop.

Among AFD, SMS, and SFS, the fastest islanding detection time was achieved using SFS in combination with the ROCOF passive protection relay. Nonetheless, the SFS method requires a more substantial alteration in active power to accurately detect when islanding occurs.

The following equation is used to implement positive

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feedback:

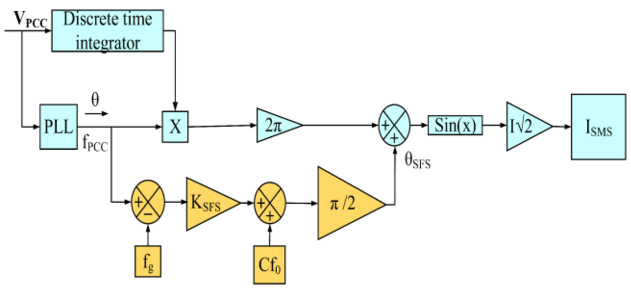

Figure 9: SFS method block diagram [6]

$$C_f = C_{f0} + k_{SFS}(f_{PCC} - f_g) \quad (16)$$

In this equation, C_f is the chopping fraction (CF). K_{SFS} is the accelerating constant, f_{PCC} is the measured frequency of the voltage at the PCC, and f_g is the frequency of the grid.

The gain K_{SFS} selection in the SFS method is a critical factor that directly influences the stability of grid-connected distributed generation (DG) systems [143]. A study in [144] analyzed the effect of SFS on system stability and indicated that elevated SFS gain (K_{SFS}) may cause instability in grid-connected DG systems, particularly when the grid is weak or the DG capacity is substantial. Therefore, further investigation is essential to reduce dependence on K_{SFS} for achieving effective NDZ elimination.

Although this method is known to have a small NDZ, it may be ineffective in detecting islanding in situations where deviations in voltage and frequency are insufficient due to a small or negligible power balance mismatch. Furthermore, the technique diminishes the output power quality of the PV inverter. Therefore, NDZ of SFS is significantly influenced by its design parameters. Therefore, determining the SFS parameters would be an optimization problem and needs an optimization technique to achieve more efficient islanding detection. The influence of the CF is examined in [143] to eliminate the NDZ in low-gain SFS schemes by applying a scheduled perturbation approach. Furthermore, [145] demonstrated that the CF can be disregarded in the SFS-based islanding detection method, as the gain (K) plays a more significant role in eliminating the NDZ. Additionally, in [140], an optimization method named the artificial immune system method is employed that generates less THD and it would have a better NDZ.

In [146], the influence of various inverter interface controllers has been analyzed regarding the anti-islanding effectiveness of the SFS scheme by employing a positive feedback gain versus islanding detection time curve. It was observed that the inverter controller's power regulation may weaken the positive feedback mechanism. Consequently, it was concluded that this method demonstrates better performance with constant current-controlled inverters compared to those operating under constant power control. Therefore, choosing an appropriate control strategy is crucial for optimizing the islanding detection capabilities of the SFS approach. Hence, choosing an appropriate controller would be a concern and needs to be considered accurately.

Generally, implementing and maintaining the positive feedback loop required for the SFS could be complex. It may involve additional components, calibration, and fine-tuning that makes it more challenging to design and integrate into practical systems. In addition, SFS may have limitations in terms of the achievable frequency range. It may be appropriate only for a specific frequency range and extending it beyond that range may result in even more significant stability and accuracy issues.

F. Sandia Voltage Shift (SVS) Method

The core principle of this method aligns with the SFS technique, which functions by enhancing positive feedback to regulate the PCC voltage. SVS similarly employs positive feedback to manage voltage amplitude at the PCC. When the primary power grid is active, any reduction in power has little effect on the PCC voltage. However, if the utility is disconnected, the PCC voltage starts to decline. This drop in PCC voltage amplitude persists due to the relationship between load impedance and the reduced current. As the PCC voltage amplitude decreases, the inverter's output current also declines, ultimately causing a further voltage drop that the under voltage protection system can detect [99]. Furthermore, fluctuations in the inverter's power output may occur in either direction, which may trigger the over voltage protection or under voltage protection UVP mechanisms, causing a trip. The active power generated by the DG during an islanding condition can be expressed as follows:

$$P_{DG} = \frac{V_{PCC}^2}{R_G} \quad (17)$$

where, V_{PCC} represents the voltage at the PCC, and R_G denotes the equivalent resistance after the PCC on the grid side [147].

In [147], a Modified Sandia voltage shift (MSVS) active scheme is developed, demonstrating significantly improved islanding detection response times. In this approach, a modification block has been introduced into the linear positive feedback of a typical SVS system. This modification incorporates an exponential-product adjustment mechanism to inject current into the grid.

However, SVS does have some drawbacks. Firstly, it slightly degrades power quality. Secondly, due to the alteration of the inverter's output power, it impacts the MPPT algorithm of the inverter, leading to a decline in its overall operational efficiency [95].

Active islanding detection methods like SMS and SVS inject voltage or frequency disturbances to detect disconnection but can interfere with MPPT algorithms such as P&O or incremental conductance [148, 149]. This interaction may degrade tracking accuracy, reduce energy harvest, and

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TABLE 3: COMPARATIVE ANALYSIS OF DIFFERENT ACTIVE ISLANDING DETECTION METHODS

IDM Method	NDZ	Detection time	Impact on Power quality	Error detection rate	Advantages	disadvantages
IM [7, 29]	Small NDZ	0.77s-0.95s	Degrades	Low	The ability to eliminate the NDZ	Degrades the power quality, it cannot be used in systems with parallel inverters
HI [7, 10]	Smallest	Few ms	Vaguely degrades	N/A	Beneficial when power balance is needed between the generator and consumer in islanding mode	Failed detection attempts when the grid experiences impedance imbalance
AFD [7, 29, 150]	Large when Qf is high	≤ 2s	Degrades	High	NDZ and balanced islanding conditions can be addressed.	Method exhibits a limited NDZ for specific load characteristics and boasts a rapid detection process
SMS [29]	Small	0.4	Degrades	Low	Highly efficient ID method for small NDZs	Decline in the output power quality and transient response issues
SFS [7, 13, 29]	Smallest	0.5s	Slightly degrades	Low	Negligible NDZ, inexpensive	Power quality and system stability continue to be concerns that can lead to undesirable system behavior
SVS [7, 29]	Smallest	N/A	Slightly degrades	Low	Easy implementation	Slightly degrades power quality impacts the MPPT
RPEED [10]	Smallest	2-5s	Slightly degrades	Low	suitable for minor load variations or no-load changes	Slow operation time may cause stability issues or equipment damages
NSCI [29]	None	60ms	Degrades (Produce harmonics [12])	Low	High degree of immunity to noise	The detection time will be increased after the controller addition

cause inverter instability, especially in weak grids, highlighting a trade-off between reliable detection and power optimization [28, 151].Future work may benefit from the development of adaptive MPPT strategies, detection-aware control algorithms, or machine learning techniques capable of distinguishing between MPPT behavior and islanding events, ultimately improving both detection reliability and energy optimization.

G. Reactive power export error detection (RPEED)

This method describes a system where an RPEED relay and a distributed generation (DG) control system work together to manage the transfer of reactive power between the DG and the grid.

The algorithm for detecting errors is implemented by compelling the DG to produce a specific level of reactive power at the PCC facilitating power exchange between the local load and the main grid. This amount of reactive power flow can only be maintained while the grid remains connected. Tripping occurs if there is a persistent deviation between the set reactive power and the actual reactive power for a specific duration. The relay is designed to trip and disconnect the DG from the main grid. This method would be more effective compared to passive methods, particularly in scenarios involving minor load variations or no-load conditions in off-grid situations. The RPEED method actively perturbs the system and ensures a more reliable detection even when load variations are negligible. In addition, it actively monitors and reacts to changes in reactive power flow. In situations where the power demand is relatively low, the combined RPEED relay and DG control system prove to be more efficient and reliable [5]. RREED has an operational time of typically 2-5 seconds and is primarily intended to serve as a backup protection mechanism. This slow operation time makes this method suitable to be employed as a backup protection system [11]. In fact, here, the time taken to detect and respond to reactive power export errors is crucial. If the response time is too long, it can result in prolonged periods of improper power flow, potentially causing stability issues or equipment damage. This method is also not applicable in inverter-based DG systems maintaining a unit power factor [14]. In addition, integration of this detection technique with existing protection and control systems may also pose technical challenges to the system that need to be studied more.

H. Negative-Sequence Current Injection (NSCI)

This active technique is developed by introducing a negative-sequence current through the voltage source controller and subsequently measuring the corresponding negative-sequence voltage at the PCC [152]. This method offers a high level of resistance to noise, is not sensitive to changes in load parameters, and requires a 2% to 3% negative-sequence current injection for islanding detection. In real scenarios, like unbalanced transients from load changes or rotating machine inrush currents, PCC voltages might

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transiently contain negative sequence components that surpass the proposed method's detection threshold and leads to false islanding detection. Therefore, the negative-sequence current is introduced using a negative-sequence controller, which serves as a complement to the voltage source converter current a voltage- sourced converter (VSC) controller. Because these negative sequence voltage components at the PCC are transient, incorporating logic to monitor their rate of change in the proposed detection method can signal to the island if the negative sequence signal stabilizes. However, this addition lengthens the detection time, and incorporating a negative-sequence controller to complement the voltage source converter current controller adds complexity to the system.

In an islanding detection method developed based on negative-sequence current injection, the controller introduces a negative-sequence current through a positive feedback mechanism upon grid disconnection. This causes the negative-sequence voltage to gradually increase, and once it surpasses a predefined threshold, the inverter shuts down [153].

The method in [153] proposes an active islanding detection method for voltage source inverters that injects a small negative-sequence voltage and evaluates the correlation with the measured PCC voltage. By using a time-invariant detection coefficient rather than voltage magnitude, the method enables accurate detection with minimal disturbance, even under unbalanced or noisy conditions. Simulation and experimental results confirm its effectiveness. The results show that the method outperforms other negative-sequence-based active techniques by minimizing power quality impact, maintaining reliability across varying grid conditions without requiring parameter tuning, and remaining unaffected by load quality factor (Q_f). However, its main limitations are increased computational complexity and slower detection speed [84]. An active IDM is introduced in [154] for PV inverters using negative-sequence voltage injection and impedance estimation at the PCC. The approach meets IEEE Std 929–2000 and is validated through simulation and experiments. Nonetheless, its effectiveness may significantly decline in systems with high PV inverter penetration and can result in false tripping under weak grid conditions [84].

Table 3 presents an overview and comparative analysis of the described active islanding detection methods discussed.

VI. Hybrid islanding detection techniques

The hybrid technique combines the features of both active and passive techniques. In fact, by combining these methods, a new category of islanding protection techniques emerges, termed hybrid anti-islanding methods. Fig. 10 illustrates a basic schematic of the hybrid method layout. In this section, the methods and challenges of several hybrid techniques that do not rely on artificial intelligence are briefly discussed. These methods can eliminate the counteraction among inverters.

A. Voltage Unbalance and Frequency Set Point (VUFSP)

This method [155] relies on monitoring both voltage imbalance and frequency deviations to identify the occurrence of islanding. In this method, monitoring the voltage unbalance corresponds to the passive component, and changing the system frequency is the active method that will be activated after the passive signature surpasses a threshold [155, 156]. To implement this method, set points or thresholds for voltage unbalance and frequency deviations are arranged based on the system characteristics. Therefore, if the measured voltage unbalance or frequency deviation goes beyond the set points for a specific duration, the islanding is detected [155]. In this method, when a voltage surge exceeds the specified threshold, the DG's frequency set point is progressively reduced from 60 Hz to 59 Hz within a span of one second. So, this could be considered a more reliable method for islanding detection. However, determining this one-second duration has been done based on empirical observations gathered from numerous simulations. Here, a short duration makes spikes harder to detect as their averages closely mimic instant values. Conversely, a long duration, like with added electronic loads, can cause false tripping as averages take time to match sudden increases in voltage. Therefore, determining this time duration would be a challenge for this system. In addition, the presence of inherent time delays in detecting voltage unbalance and frequency deviations, as well as verifying an islanding event, can potentially hinder the efficiency of the detection system, particularly in situations where rapid disconnection is required to maintain system stability.

B. Average Rate of Voltage Change (ARVC) and Real Power Shift (RPS)

This method [157] employs Reactive Power Shift (RPS) only when the passive technique, ARVC, is unable to effectively distinguish between the grid-connected mode and an islanding scenario. In fact, this method effectively removes the necessity for injecting active disturbances, which typically are used in other active techniques. By using this method, only the DG system's real power is modified, so, it can be ensured that DG continues operating at a unity power factor. Unlike positive feedback methods, where all DG units collectively inject perturbations into the system, this technique involves only adjusting the real power of a single DG.

Additionally, it can effectively differentiate islanding from other events in the distribution system and it removes the need for injecting disturbances. The suggested approach has undergone validation within a power distribution network situated in Aalborg, Denmark [157]. Moreover, the islanding detection of this method remains effective even when the load and generation are closely balanced. However, if islanding occurs in a perfectly matched system, the method may fail to detect it, and therefore, any later fluctuations in load or power

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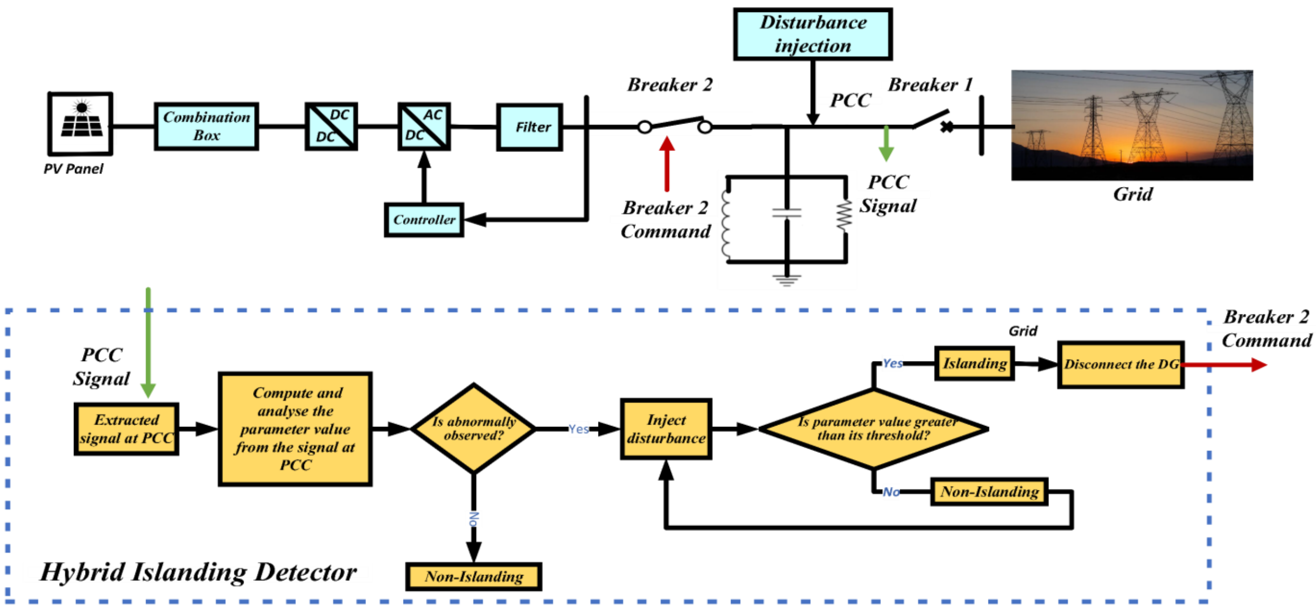

Figure 10: Hybrid islanding detection technique layout for PV system

generation will cause voltage variations, leading to the detection of islanding [157].

C. SFS and Q-f droop curve

This method [158], combines the features of the SFS and Q-f droop curve methods. The Q-f droop curve functions by monitoring variations in the correlation between reactive power and frequency within the load, without directly affecting the system. As it observes system parameters to identify islanding conditions, it is classified as a passive method. However, the SFS detects islanding by actively modifying the system's operating conditions, specifically adjusting the frequency in response to the system's behavior. Because it directly influences the system, it is categorized as an active method. Here, the SFS method is applied by adjusting the inverter's current angle. The optimal SFS gain is determined using an analytical formula in conjunction with the Bacterial Foraging Algorithm (BFA), which is employed to explore and identify the gain value that effectively eliminates the Non-Detection Zone (NDZ). However, to enhance the SFS method's efficiency and minimize NDZs, it can be combined with the Q-f droop curve method. As discussed earlier, generally, DGs typically designed to function at a unity power factor, delivering only active power without producing reactive power. In the islanding situation, if a DG is configured to provide no reactive power, the system frequency will drift in a manner that the load consumes no reactive power either. This method has been utilized for islanding detection by incorporating a Q-f droop characteristic into the DG interface [159]. The proposed concept centers on analyzing the Q−f characteristic of both the load and the DG. This analysis aims to identify the optimal operating characteristics for the DG, which facilitates effective islanding detection. The Q−f droop is specifically selected to ensure the DG operates steadily while connected to the grid. The proposed concept centers on analyzing the Q−f characteristic of both the load and the DG. This analysis aims to identify the optimal operating characteristics for the DG, which facilitates effective islanding detection. The Q−f droop is specifically selected to ensure the DG operates steadily while connected to the grid. However, it is designed to deviate from stability when an islanding scenario occurs. Here, again determining the best value of k would be a challenge for the SFS method. A larger value of k could lead to unwanted tripping and significantly heighten the sensitivity of the SFS method to any disturbances occurring within the distribution system.

D. SFS and ROCOF

In this approach [59], the active method involves the optimized Sandia Frequency Shift (SFS) technique, while the passive method utilizes the ROCOF [59]. In this technique, the activation of the SFS method occurs solely when the ROCOF relay suspects an islanded condition. To further detect the islanding condition, the relay measures over multiple cycles, typically ranging from 2 to 50 cycles. Subsequently, the signal necessary for islanding detection is calculated and transmitted to a low-pass filter. One of the most important features of this hybrid method relies in the application of the SFS method. Due to the intermittent operation of SFS in this approach, the power quality of the system is expected to experience significant enhancements. In addition, as SFS operates intermittently, higher values for k can be selected without worrying about false protection trips or power quality issues. In comparison with the SFS, this hybrid method reduces NDZ, increases response speed, and performs more efficiently when

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it is applied to a multi-DG system [59]. Another important point of combining ROCOF and SFS is maintaining a minimal ROCOF threshold level. Therefore, islanding events can still be detected even in cases where the DG and load capacities are nearly equal [59].

On the other hand, the presence of grid disturbances and grid frequency fluctuations can interfere with the precision of the islanding detection procedure. In addition, the method may face challenges in detecting islanding events during transient conditions when frequency deviations occur temporarily. Furthermore, the method's performance could be influenced by changes in the system configuration, the addition of new DGs, or variations in load patterns. Still, the efficacy of the SFS method hinges on the magnitude of its positive feedback gain k. A higher value of k corresponds to quicker islanding detection speed and a smaller NDZ. The primary challenge with the ROCOF method arises when detecting islanding becomes problematic due to the proximity of load and generation capacities within the isolated system. Additionally, precise attention is essential when establishing thresholds for the ROCOF relay. Setting the threshold too low might trigger unnecessary trips of DG, while a threshold set too high could fail to detect islanding. [59].

In another hybrid ROCOF and SFS unconventional method, SFS is employed as the active islanding detection technique and the method utilizes the ROCOF relay as the passive approach. Its primary innovation lies in applying the Maximum Likelihood Estimation (MLE) method to determine ROCOF, rather than relying on the traditional Phase-Locked Loop (PLL)-based estimation. The aim is to enhance detection performance across diverse scenarios by achieving rapid response while maintaining high accuracy [160, 161].

E. ROCOV and Duty Cycle Disturbance Injection (DCDI)

This method presents a two-level algorithm for detecting islanding in GCPV Systems. Monitoring ROCOV involves observing changes in the system voltage without directly influencing it, making this a passive method. However, creating a disturbance in the duty cycle actively changes the system's behavior to facilitate islanding detection, which categorizes it as an active method. In the initial phase of the proposed IDM, a disturbance is initiated in the duty cycle of the DC/DC converter when the measured ROCOV exceeds a predefined threshold. This disturbance deliberately alters the GCPV system operating point, deviates from the optimal MPP, resulting in concurrent high negative values for both ROCOV and ROCOP at the second level during islanding conditions [79]. Therefore, at the second level, ROCOV and ROCOP are measured, and if they surpass their thresholds, islanding is detected. This means the disturbance prompts a sudden decrease in active power output, consequently, causing a decline in the PCC voltage during islanding incidents. However, this disturbance minimally affects the output voltage when the distributed generation operates in parallel with the grid.

According to various reports, the ROCOV can be effectively utilized in AC microgrids for detecting disconnection from the main grid [162]. Therefore, in this method, when ROCOV exceeds a predetermined threshold, a disturbance is initiated in the duty cycle in the following equations:

$$\begin{cases} D_{new} = D_{MPP} - 0.5, & D_{MPP} \geq 0.5 \\ D_{new} = D_{MPP} + 0.5, & D_{MPP} < 0.5 \end{cases} \tag{18}$$

where D_{new} is the new duty cycle, and D_{MPP} denotes the duty cycle associated with the MPP.

The short-duration disturbance is deactivated for a specified duration to reinstate the MPP, typically set at 1.8 seconds. Additionally, an intentional 0.2-second delay is introduced to prevent nuisance tripping when non-islanding events occur. Furthermore, D_{new} as defined in (18), aims to achieve the maximum possible deviation from the MPP.

The comparative evaluation of the proposed strategy against several existing IDMs emphasizes its progress in terms of simple and cost-effective implementation, as well as self-contained and straightforward threshold determination. In addition, this method can detect islanding within 510 ms [79].

However, this method can have some issues that need to be studied more. This approach can identify islanding except within a narrow range of -0.4% to 0.4% in terms of rate of change of active power. Therefore, this method still has an NDZ. In addition, there are three threshold settings in this method that can be a challenge for determination and nuisance tripping. The ROCOV threshold (Th1) in the first stage triggers the disturbance to address MPP loss. The ROCOV and ROCOP thresholds (Th2 and Th3) in the second stage categorize incidents as either islanding or non-islanding events. Furthermore, this method exhibits small power quality deterioration [163].

F. Lissajous Pattern (LP) and Reactive Power Injection (RPI)

The Lissajous Pattern (LP) parameter is employed for rapidly detecting electrical faults. It can promptly detect frequency or phase jumps during transient states [164]. LP also can be used for quick unintentional islanding detection of multiple DGs, even in scenarios of zero power mismatch or power balance [165]. LP does not directly affect the system, which classifies it as a passive method. The method solely necessitates the fundamental components of voltage and current phasors at the PCC, acquired through Moving Window Discrete Fourier Transform (MWDFT). This method effectively tackles several issues such as applicability for both single DG and Inverter-Interfaced DGs, handling failure even during perfect power balance conditions, reducing dependency on preset thresholds, and minimizing high error detection rates. However, the single-stage method presented in [165] lacks the ability to differentiate nuisance tripping cases. Additionally, the work does not include a mathematical

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TABLE 4: COMPARISON OF VARIOUS HYBRID ISLANDING DETECTION METHODS

IDM Method	NDZ	Detection time	Advantage	Disadvantage
VUFSP	None	0.21s	Less destabilize the utility grid, only the DGs near the load switching event adjust their frequency set points.	Efficiency can be decreased because of the delays in detecting voltage imbalance and frequency changes
ARVC and RPS	Relatively small NDZ [166]	N/A	Islanding detection remains effective even in cases where there is a close match between the load and generation	Method can fail when demand and generation perfectly match
SFS and Q-f droop	Small	N/A	There's no need to raise the gain factor of the SFS method to improve detection	The system's power quality might pose concerns, particularly regarding threshold detection [7, 21].
SFS and ROCOF	Smaller that SFS	0.2s	Multi-DG systems application and fast detection with high accuracy	Allocating trip boundaries can be challenging in specific cases [7]
ROCOV and DCDI [79]	Near zero NDZ [163]	Within 510 ms [79]	Establishing self-standing thresholds ensures no adverse impact on output power quality, maintaining simplicity and cost-effectiveness [79]	Might encounter difficulties detecting islanding events during transient conditions characterized by temporary frequency deviations [79]
LP and RPI [167]	Near Zero	Less than 160ms [167]	This two-stage verification process effectively eliminates the ambiguity between nuisance tripping phenomena and an actual islanding event	N/A

analysis for setting the threshold of the LP parameter. Furthermore, the impact of power quality and other disturbances on LP-based detection remains unexplored [167]. In [167], an islanding detection technique has been proposed based on assessing the LP due to active power absorption and reactive power injection (a hybrid approach). The technique utilizes a second-order general integrator-frequency locked loop to preprocess the voltage waveform, reducing uncertainty across various power quality scenarios and working conditions. The LP is used to identify islanding conditions based on the frequency variation of the fundamental voltage. The detection parameter for evaluating frequency variation is selected as the minor axis of LP, and its threshold value is derived. The implementation of two-stage verifications enhances the reliability of the detection method.

An overview and comparison of the described hybrid islanding detection methods are provided in Table 4.

VII. Discussion

In this section, a discussion and comparison are conducted among passive, active, and hybrid methods, with attempts made to highlight their features and challenges. The challenge with passive methods lies in determining the most suitable threshold [168, 169]. Here, balancing the NDZ and quality factor is crucial. The passive techniques offer fast and simple implementation without system disturbances. However, a notable drawback is its considerable NDZ [170], which remains a primary issue even when utilizing traditional passive or smart passive techniques [171, 172]. Passive methods can be susceptible to false alarms, especially during transient events. In contrast, low energy consumption is generally a feature of passive methods as they rely on system parameters, and they are generally simpler and more cost-effective. Since the system signatures associated with passive methods are always present in any grid-connected system, it is crucial to conduct comprehensive research on them to select the most suitable strategy for islanding detection [173].

While active methods boast smaller NDZ, they often compromise the system's power quality. Some can detect islanding without affecting power quality, but this demands multiple controllers, escalating implementation complexity, and cost compared to other local techniques [174, 175]. Active methods may have a higher false alarm rate if not appropriately configured. However, these methods stand out for their fast response, enhanced reliability, and potential to reduce the NDZ [168]. It should be noted that while a smaller NDZ is preferable for enhanced response in islanding detection, it tends to inversely impact the Qf factor. Achieving optimal outcomes across all parameters is the current focal point in this research domain.

Hybrid methods are produced based on the combination of passive and active techniques. The hybrid strategy aims to leverage the strengths of diverse techniques, mitigating potential limitations, and enhancing the overall effectiveness of the islanding detection system. Hybrid methods combine adaptability by incorporating features that respond to both dynamic and steady-state conditions. These methods demonstrate less operation failure. By employing these detection techniques, hybrid methods enhance the overall reliability of islanding detection. Hybrid methods can be designed to optimize energy consumption by selectively utilizing active methods when necessary. In addition, their complexity and cost depend on the particular blend of passive and active characteristics. In summary, each islanding detection technique comes with its own benefits and drawbacks. The selection is determined by the unique requirements and constraints of the power system in question and these comparisons could be utilized to conduct further research on these techniques and their weaknesses, aiming to enhance islanding detection efficiency and system reliability.

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TABLE 5: A COMPARISON AMONG PASSIVE, ACTIVE AND HYBRID METHODS

Characteristic	Local Method		
	Passive	**Active**	**Hybrid**
Principle of operations	Utilizes monitoring for voltage, current, frequency, harmonics at PCC	Used DG disturbances to steer the system towards frequency/voltage trip limits	passive and active method combination
Response time	short	Larger than passive	Longer than active methods
Non detection zone	Large	small	small
Error detection ratio	Higher than active method	Decrease error detection ratio	Decrease more than active methods
Operation failure	Possible when there are minor power mismatches between the utility and local load	Possible when Q factor is high	The possibility is less than active and passive methods
Impact on the distribution network	None	Effective on the power quality and voltage fluctuations	Lower than active method
Effectiveness	The efficiency will be decreased in the balanced condition	Islanding can be detected even if the system is balanced condition	High, effective to be applied in complex systems
System cost	Low (needs minimum hardware)	Medium due to the requirement for extra components.	High
Multiple DGs operation	Possible	Impossible	Less compared to active
Affected by the number of connected inverters.	None	Yes, effectiveness in multiple DG systems would be concerned	Yes
Effect on power quality	None	Depends on the employed method, but it is possible to degrade.	Very low

A detailed comparison is made in Table 5 among these three groups of methods.

VIII. Conclusion

In this paper, an extensive review of islanding detection techniques, with a focus on solar PV systems, has been presented. The essential characteristics of local detection methods were analyzed, and the operational principles of passive, active, and hybrid approaches were systematically examined. Key challenges such as non-detection zones, detection time, false tripping, and sensitivity to load variations were discussed in detail. By comparing performance metrics and analyzing implementation trade-offs, this study contributes to a clearer understanding of detection reliability across varying grid conditions. The review offers a consolidated foundation that supports researchers in selecting appropriate methods and recognizing critical limitations across different scenarios. Ultimately, this work supports the improvement of islanding detection strategies to make them more reliable and better suited to current power system requirements.

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Farshad Aslani received his MS degree in 2012. He is currently pursuing a Ph.D. in Electrical and Computer Engineering at The University of Alabama, Tuscaloosa, USA. His research focuses on islanding detection, renewable energy technologies, and the protection of inverter-based power systems. He has several years of experience as a professional automation engineer and university instructor, combining industry expertise with academic teaching. Throughout his academic journey, he has authored multiple journal papers and actively serves as a reviewer for several esteemed journals.

Shuhui Li (S'99–M'99–SM'08) received the B.S. and M.S. degrees in electrical engineering from Southwest Jiaotong University, Chengdu, China, in 1983 and 1988, respectively, and the Ph.D. degree in electrical engineering from Texas Tech University, Lubbock, TX, USA, in 1999. He was with the School of Electrical Engineering, Southwest Jiaotong University, from 1988 to 1995, where his fields of research interest included electrified railways, power electronics, power systems, and power system harmonics. From 1995 to 1999, he was engaged in research on wind power, artificial neural networks, and applications of massive parallel processing. He joined Texas A&M University, Kingsville, TX, USA, as an Assistant Professor, in 1999, and an Associate Professor in 2003. He joined the University of Alabama, Tuscaloosa, AL, USA in 2006 and is now a Full Professor. His current research interests include renewable energy systems, power electronics, power systems, electric machines and drives, and applications of artificial neural networks in energy systems.

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