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A critical assessment of islanding detection methods of solar photovoltaic systems

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ABSTRACT

This study identifies inadvertent islanding in electrical networks incorporating Distributed Generators (DGs). With the global rise of DG deployment, it becomes imperative to scrutinize their influence on the network and guarantee that anti-islanding protective systems can accurately discern such conditions. However, it is equally important to prevent false alarms that might result in unwarranted DG disconnections during unrelated incidents. Fulfilling these stringent technical prerequisites is a fundamental aspect of ensuring the safe and dependable functioning of the electrical grid. Consequently, this investigation aims to comprehensively explore the scholarly discourse surrounding islanding detection methodologies for distributed generators. The manuscript assesses various methods for detecting islanding phenomena, spanning passive, active, and remote techniques. These include under/over voltage, Sandia frequency/voltage shift, Sandia frequency shift, and under/over frequency protection mechanisms. It offers an exhaustive review of diverse techniques to identify islanding in distributed generation networks, studying their respective merits, demerits, and overall efficacy in pinpointing this condition. Thus, this research holds paramount importance in bolstering the dependability of electrical networks incorporating DGs. It aids in advancing anti-islanding protection systems that satisfy crucial technical specifications.

Nomenclature

Abbreviations

AI	Artificial Intelligence
AC	Alternating current
AFD	Active frequency drift
AFDPF	Active frequency drift positive feedback
ANN	Artificial neural network
CB	Circuit breaker

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DC	Direct current
DER	Distributed energy resources
DFT	Discrete Fourier transform
DG	Distributed generation
ESS	Energy storage system
FT	Fourier transform
FFT	Fast Fourier transform
ML	Machine learning
MDW	Moving data window
NDZ	Non-detection zone
PCC	Point of common coupling
PLC	Programmable logic controller
PLL	Phase-locked loop
PV	Photovoltaic
RES	Renewable energy sources
RTU	Remote terminal unit
SCADA	Supervisory control and data acquisition
SFS	Sandia frequency shift
STFT	Short-time Fourier transform
THD	Total harmonic distortion
OUV	Over/under voltage
OUF	Over/under frequency
WT	Wavelet transform

Variable /Parameter

S_1	Circuit breaker at utility side
S	Circuit breaker at photovoltaic side
P_I	Active power supplied by photovoltaic
Q_I	Reactive power supplied by photovoltaic
P_L	Load active power demand
Q_L	Load reactive power demand
R	Resistive load
L	Inductive load
C	Capacitive load
V	Voltage across the load
ω	Angular frequency
V_{max}	Maximum threshold voltage
V_{min}	Minimum threshold voltage
f_{max}	Maximum threshold frequency
f_{min}	Minimum threshold frequency
V_{dc}	DC- link voltage
V_{grms}	Grid root mean square value of voltage
I_{grms}	Grid root mean square value of current
I_{inv}	Inverter current
I_m	Inverter current amplitude
θ	Inverter current initial phase angle
I_{ref}	Inverter reference current
t_z	Zero-conduction time
c_f	Chopping factor
T	Utility grid voltage period
k	Positive feedback gain
f_n	Nominal grid frequency
V_{inv}	Inverter voltage
Z	RLC load
I_{dis}	Disturbance current
V_e	Error voltage signal

1. Introduction

The surge in global population and subsequent electricity demand necessitates a transition towards sustainable energy sources that mitigate environmental challenges [1]. The integration and progression of renewable energy sources (RESs) such as geothermal, hydro, solar, and wind energy offer potential solutions to the escalating electricity demand while endorsing environmental conservation [2]. Solar energy, harnessed through photovoltaic (PV) panels, emerges as an abundant and infinite energy source. With the declining cost of PV technology, solar power is becoming a progressively viable choice for electricity generation. Likewise, wind power, captured via wind turbines, stands as a prospective RES, capable of potentially contributing a significant fraction to the world's electricity requirements [3]. Hydropower, a longstanding sustainable energy source, utilizes flowing water to generate electricity. Despite specific detrimental environmental impacts, like modification of natural river systems and influence on fish populations, proper management can render it a reliable and clean energy source [4]. Geothermal energy, which involves harnessing the heat from the Earth interior, is also a promising renewable energy source. It can potentially provide reliable and sustainable energy, particularly in areas with high geothermal activity [5].

As per human standards, solar energy is seen as an inexhaustible source, making it a frontrunner in renewable power sources [2,6]. It can be employed directly for heating or electricity generation, proving ideal for regions with abundant solar radiation [7]. Solar PV has gained universal acceptance thanks to significant advancements in manufacturing more efficient photovoltaic cells and power electronics, enabling the creation of converters [3,8]. These technological advancements have significantly improved the efficiency and reliability of solar power systems. As a result, solar energy has several advantages over traditional fossil fuels, including minimizing greenhouse gas emissions and dependence on fossil fuels and promoting energy independence [9,10]. Solar power systems also require minimal maintenance and have a longer lifespan than traditional power systems [11]. As a result, solar energy use potentially provides a dependable, sustainable, and eco-friendly energy source capable of meeting escalating global energy needs [12].

The grid-tied PV systems result in the formation of active distribution systems to improve the performance of the electrical network [13]. These systems fundamentally alter the traditional power system structural design [14,15] since power flow becomes bidirectional, which allows for the increased energy supply from distributed generations (DG)s [16]. However, the dynamic characteristics of DG systems differ significantly from the large generators in the generation system and can cause instabilities in the electrical power system [16]. Therefore, control algorithms used in the converters are of fundamental importance to guarantee the safe and reliable operation of DGs [17]. These algorithms have a pivotal function in upholding the stability of the electric power grid and ensuring the precise functioning of photovoltaic (PV) systems. The control algorithms must be carefully designed and optimised to account for the dynamic characteristics of DGs and ensure smooth integration into the electrical power system [18]. Advanced and intelligent control methods, including fuzzy logic control and neural network control, can significantly enhance the performance of photovoltaic systems. These techniques can improve the accuracy of the control algorithms, maximise system efficiency, and minimise the impact of DGs on the electrical power grid. In this context, they are integrating PV systems with the electrical grid, resulting in active distribution systems, which require careful consideration of the control algorithms used in the converters. Intelligent control techniques can provide an accurate platform for the PV system to perform excellently [19].

Islanding represents another critical factor in DG system operation [20]. Islanding refers to a situation where a part of the power distribution system, consisting of loads and generation systems, disconnects from the leading network due to a fault in the primary electrical grid but continues to operate independently [21]. This situation can lead to numerous complications [22], such as large voltage and frequency deviations, reclosure issues, and safety hazards for system workers [23]. Islanding can occur due to the loss of synchronism [24,25] or the loss of connection between the DG system and the central power grid [26,27]. Therefore, it is crucial to implement efficient anti-islanding protection mechanisms capable of identifying and disconnecting the DG system from the power supply system in case of an islanding event [28]. Various techniques, such as passive, active, hybrid, and communication-based strategies, are available to detect islanding events [29]. Passive methods identify changes in system variables like frequency or voltage, whereas active techniques introduce a signal into the power network to detect system response variations. Hybrid strategies merge passive and active approaches to enhance detection accuracy and reduce false positives. Communication-based methods employ intelligent grid technologies for real-time system control and monitoring. Signal processing and Artificial Intelligence (AI) have also found applications in islanding detection. In the context of DG operation, islanding is a significant concern, making it essential to implement effective anti-islanding protection systems to ensure the safe and reliable operation of the power supply system [30]. The effectiveness of various islanding detection techniques must be evaluated to ensure their successful implementation in the power supply system.

Islanding might also transpire when a balance between load and generation in the system exists while the primary power supply becomes inaccessible. Such a situation could be attributed to system protection failures during faults at the utility or when distributor disconnection motives are not electrically based. An example of an accidental tripping instance is where the protective device severs the system under regular operation conditions [31]. The efficacy of islanding detection is contingent upon the magnitude of the power flow within the network during the fault event [27]. Smaller power flows extend the detection time, with the most challenging case arising when the local load's power demand precisely matches the energy output of the induction generator [32].

Multiple existing literature studies investigated the performance of different anti-islanding techniques focusing on grid-connected PV systems by addressing their strengths and limitations [33–37]. The performance of active methods is compared in the case of power equilibrium between load and generation. These showed the ability of operational strategies to minimise the non-detection zone to almost zero and provide a brief trip time. The examined methods were current injection, active and reactive power variation, and capacitor insertion methods [33]. Another research work also discusses active strategies; however, the paper focused on the most well-known active methods: active frequency drift, Sandia frequency shift, Sandia voltage shift, and Sandia voltage shift. The study emphasised the short trip time that active methods offer and illustrated the robustness of these methods under fault-ride-through mode, various load types, and solar irradiance changes [35]. Experimental setup proved active methods detection capability over passive methods. Yet, it was shown that power quality is degraded when using active methods due to harmonic distortion or displacement power factor issues [37]. Besides, non-detection zone, trip time, power quality, system cost and operation under multi-DG units are significant factors in analysing anit-islanding methods [36,38]. It is crucial to consider both the setup and operational expenses to avoid a trade-off between cost-effectiveness and maintaining system quality [36]. In case of significant penetration of DG units, communication-based methods can be more effective, especially when considering intelligent grids [39]. The conventional hierarchy of islanding detection methods categorises them into local and remote groups, where local categories contain passive, active and hybrid. Remote islanding detection methods are subdivided further in some papers into communication-based and utility methods, including impedance insertion [34,36].

Some recent studies addressed modern islanding detection techniques [40–42]. Signal processing-based islanding detection methods are usually employed to enhance the performance of passive strategies. Thus, some studies considered them a subdivision of

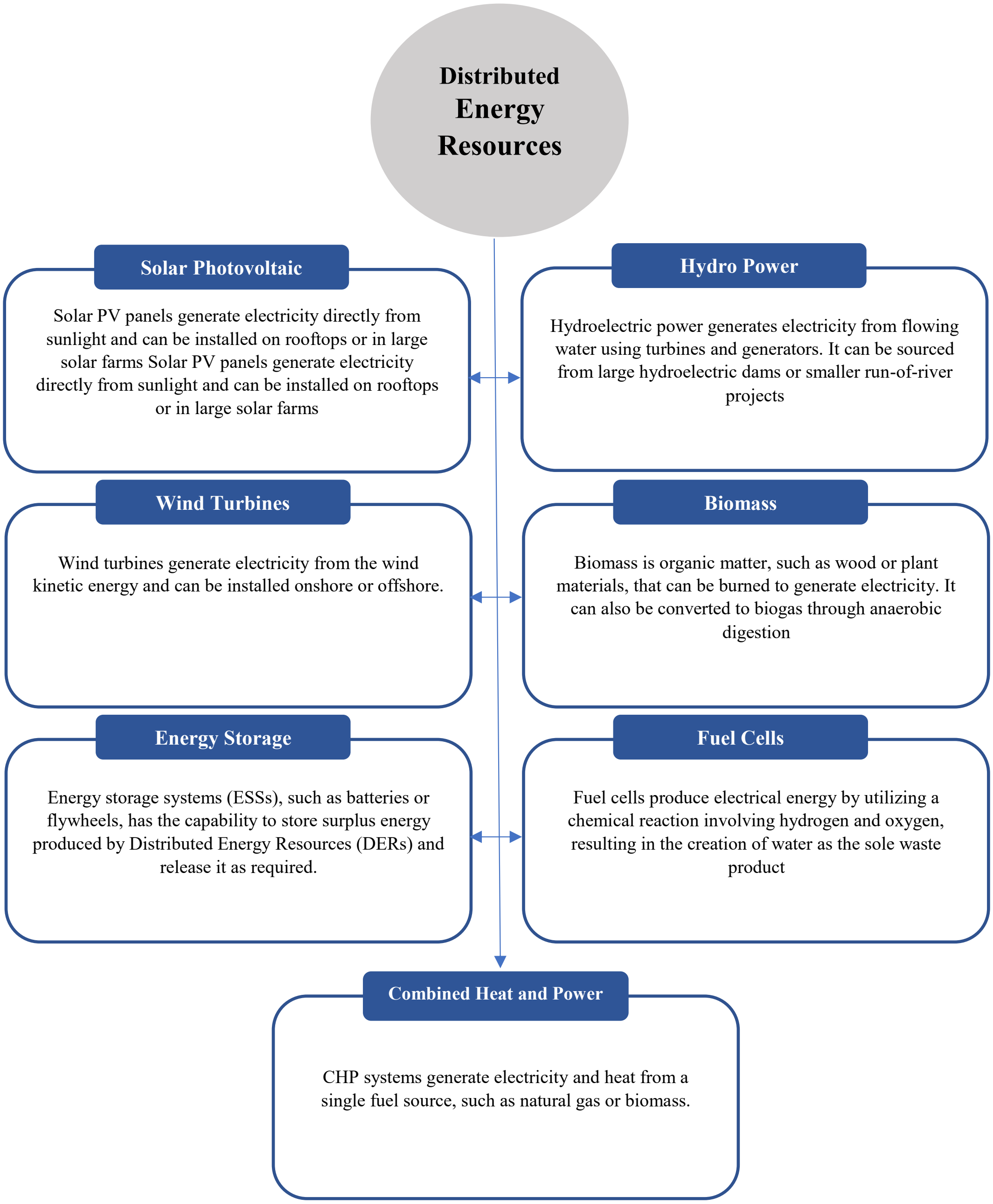

Fig. 1. Examples of distributed energy resources.

the passive method category [40,41]. On the contrary, the islanding detection methods hierarchy was updated in some studies to include a signal processing category besides local and remote groups [42] or to combine signal processing and AI as one group. These recent studies provided additional comparison factors like practical feasibility and adoption simplicity [41,42] and methods accuracy [41] while offering a detailed analysis of the methods. Gaps have been observed in assessing a critical analysis of PV system islanding detection methods for innovative grid environments and their future scope for autonomous power grid applications. Therefore, this study scrutinizes the performance of passive, active, remote, and intelligent islanding detection techniques for Solar PVs. Each of these four categories characterises the unique contributions of every method to islanding detection. This study assesses different methods and classifies them into four categories to provide a critical assessment for islanding detection approaches in the innovative grid environment. The first category, passive techniques, encompasses methods that do not deteriorate power quality as they abstain from introducing distortions into the inverter operational parameters. In contrast, active techniques enhance network interruption detection by reducing the non-detection zone (NDZ) by injecting minor distortions in inverter operating parameters. These parameters could be the phase discrepancy between the output current, the point of common coupling (PCC) voltage, the output current waveform, and current harmonic distortion. The remote methods demonstrate the importance of applying communication-based strategies for fast, accurate, real-time authentication of islanding detection for the grid-tied PV system. Additionally, the study bestows invaluable insights regarding applying intelligent techniques, such as signal processing, AI and more, in the islanding detection process. These practical approaches can be effectively amalgamated with existing islanding detection methods to augment the overall detection reliability. The paper further discusses the prospective implementation of these techniques within intelligent grid environments.

The remaining part of this research study can be summarized as follows: Section 2 presents the system description of distributed energy resources. Section 3 offers modelling based on the analysis of islanding. Section 4 assesses the various islanding detection methods in the innovative grid environment. Section 5 discusses methodologies and provides a future perspective. Section 6 presents the conclusion and future advancement in islanding detection.

2. Distributed energy resources

Distributed energy resources (DERs), also known as DGs, are generation units of low or medium-voltage generation units that can be located on the consumer and supplier sides [17]. The utilisation of DERs converts conventional large-scale distribution networks into smaller entities. Therefore, it is anticipated that DERs enhance the quality of the provided electricity alongside its reliability and reduce losses [43]. However, integrating DERs enforces strict requirements on both ends of the power system, the utility and consumers [44], to regulate the grid operations besides enhancing protection; hence, system complexity is increased [45]. Furthermore, DERs offer a bidirectional flow of electricity. Yet, the distribution systems are built as radial networks that supply power in a single direction [44], which may raise the need for reconfiguration of the existing systems. DERs can range from traditional energy resources depending on fossil fuel combustion to the most recent version of renewable energy resources [46]. Fig. 1 shows several types of DERs that can be integrated into a microgrid system.

Each DER has unique advantages and disadvantages, depending on location, availability, and cost. Therefore, the optimal mix of DERs in a microgrid system depends on the specific needs of the community or facility it serves and the energy resources available in the surrounding area. Besides, hybrid energy storage assists in the smoother transfer of diverse DERs when connected to the power grid [47]. The application of supercapacitors and conventional energy storage systems in DERs brings a covering opportunity for energy transit in the microgrid environment. However, this scheme always requires sufficient stored energy and control coordination to guarantee the smooth transfer of the microgrid. The islanding detection methods applied in such a system with PV integration increase the overall performance and ensure comprehensive equipment protection of microgrids [48].

2.1. Renewable energy

The energy sector predominantly depends on the combustion of fossil fuels, with specific sectors like transportation reliant on oil for more than 90% of their energy consumption. Furthermore, the undeniable influence of the oil industry on the global economy has spurred lobbying endeavours in support of fossil fuel utilisation [49]. Nonetheless, curtailing the percentage of power generated from fossil fuels is imperative to offset their inevitable depletion and consequential impacts on climate change [50]. The International Energy Agency has advocated reducing fossil fuel consumption from 70% to less than 20% by 2050, compared to 2010. This reduction regarding fossil fuels is crucial in mitigating their dwindling availability and contribution to global warming [51]. RESs, including hydro, solar, wind, and others, exhibit unique characteristics and necessitate specialized equipment and infrastructure for grid integration. Despite these requirements, the benefits of RESs are considerable. They hold the potential to substantially decrease greenhouse gas emissions, enhance energy security, and play a significant role in climate change mitigation [52].

2.2. Microgrid and solar photovoltaic

Microgrids have evolved as a potential structure for integrating distributed energy resources, aiming to fulfil the diverse energy needs of various communities [51,53]. Such requirements encompass enhancing power system resilience to accommodate operational modifications and ensuring swift recovery following natural disasters, as well as bolstering the capacity of the electrical system to provide continuous power to all consumers [51,54]. A primary impetus behind adopting microgrids is addressing environmental concerns, given that distributed energy resources can help reduce carbon emissions. Economically, microgrids can decentralize power generation, thus eliminating substantial transmission costs [55]. The operational flexibility of microgrids is another merit [54]. Microgrids can function independently of the primary power grid, providing power to a specific area or community during power outages or disruptions. Alternatively, they can be interconnected with the main grid, facilitating energy sharing and enhanced system efficiency. Microgrids provide a promising solution to improve the resilience and reliability of the power system while addressing environmental and economic concerns [56]. Their adaptability and versatility appeal to communities and businesses aiming to secure their power supply and reduce their carbon footprint.

Microgrids exhibit remarkable operational flexibility, contributing to enhanced efficiency and reliability. They can be designed to operate in either interconnected or independent (islanded) modes, depending on the facility's specific requirements. For example, in grid-connected mode, the microgrid can link with the main power network and efficiently exchange power by exporting or importing as needed. The microgrid can also partake in demand response programs, modulating its power output based on grid conditions and market signals to aid in overall system balance [19,56]. In islanded mode, the microgrid operates autonomously from the broader power network, supplying power to a specified location or community during power outages or other disruptions. This is accomplished through energy storage systems (ESSs), distributed energy resources, and microgrid control systems that can regulate power supply and demand in real-time environments [57,58].

Solar PV systems are among the most prevalent and widely utilised distributed energy resources in microgrid systems. Solar PV converts sunlight directly into electricity, rendering it a clean and renewable energy source [3]. The energy produced from solar PV can power homes, businesses, and other facilities, with excess stored in batteries when sunlight is scarce [59,60]. Solar PV can be coupled with other DERs, such as wind turbines, ESSs, and backup generators, within a microgrid system to form a more robust and reliable energy system [61,62]. The microgrid control system optimizes energy flow using various resources to meet the community's or facility's demand [63]. A key advantage of solar PV in a microgrid system is its scalability [56]. Solar panels can be effortlessly installed and expanded, permitting gradual power generation increases as required. This also renders it a cost-effective solution for remote or off-grid communities lacking connection to the main power grid.

Additionally, the environmental benefits of solar PV within a microgrid system are noteworthy. Solar PV generates electricity without greenhouse gas emissions, making it a vital instrument in carbon emissions reduction and climate change mitigation efforts. Solar PV is a critical component of microgrid systems, providing a clean, renewable, and scalable energy source that enhances the power system's reliability and resilience [3].

Islanding is a significant feature of microgrids, enabling the continuous provision of power during grid outages, thereby minimizing the impact on essential infrastructures and services [64]. Operating a microgrid in islanded mode can boost system efficiency, as power is locally generated and consumed, reducing long-distance power transmission and distribution requirements. A solar PV and microgrid island constitute a self-sufficient system that merges solar PV panels and other distributed energy resources with a microgrid control system. This system can function independently of the main power grid, supplying electricity to specific locations or communities during an outage or disruption [65]. In such an island, solar PV panels convert sunlight into electricity, which can also be stored in batteries for future use [66,67].

The microgrid control system oversees the energy flow and optimizes the utilisation of various resources to meet the demand of the community or facility [68,69]. One of the notable advantages of a solar PV and microgrid island is its high resilience and reliability [70,71]. As it operates autonomously from the primary power grid, it can ensure a steady supply of electricity to vital infrastructure and services during power outages or other disturbances [72]. A solar PV and microgrid island offer potential benefits in terms of enhanced energy security and independence. By generating and consuming power locally, communities can reduce their dependence on the main power grid, mitigating risks associated with cyber-attacks or physical infrastructure damage [10,51]. Altogether, a solar PV and microgrid island represents a promising solution for communities and facilities seeking to enhance their energy resilience, reliability, and security while reducing their carbon footprint [73]. However, it's important to note that the unexpected islanding of solar PV can present challenges [74].

2.3. Cause of islanding in PV system

Islanding can be bifurcated into intentional and unintentional types [75]. Intentional islanding takes place when the managing entity of the electrical system, or the concessionaire, purposefully isolates a portion of the system. This is typically achieved through one or more distributed generators. Intentional islanding aims to supply power to a specific area or vital loads even when the primary grid is not accessible, making it a planned and controlled process. Conversely, unintentional islanding is unexpected and unplanned. It arises when the electricity supply to a specific area or grid segment is interrupted for diverse reasons. These may include equipment malfunction, grid faults, severe weather conditions, or other unexpected events. As a result, the isolated section continues to function independently as an island, oblivious of the disconnection from the main grid [76].

The inability to detect an island or delayed detection and disconnection of a DG can result in significant power quality and security issues [90]. The formation of unintentional islanding is undesirable due to the numerous problems to which the system can be exposed, including:

- Power Quality Concerns - In an unintentional island, power quality may be incompatible with required standards and beyond the distributor's control. This may lead to issues like voltage and frequency fluctuations, harmonics, and other concerns that can hamper the operation of electrical equipment.
- Reduction of Short Circuit Levels - Unintentional islanding can decrease short circuit levels, potentially resulting in poor coordination among the protected systems in the isolated area. This may cause further power quality issues and complicate the safe maintenance of the electrical system.
- Life Risk During Maintenance - Unintentional islanding can pose a significant risk to maintenance personnel due to the presence of energized areas that may have been overlooked.

Table 1 delineates various unintentional islanding incidents that necessitate more prevention measures for PV systems. Therefore, it's vital to deploy effective anti-islanding protection systems capable of detecting and isolating the DG system from the power supply system during an islanding event. The utilisation of sophisticated control algorithms and techniques can enhance the performance of anti-islanding protection systems and ensure their seamless integration into the electrical power supply system. In addition, system modelling is essential for controlling and protecting microgrids under varying operational conditions.

3. Model for the study of islanding

Fig. 2 showcases a grid-connected PV system model, which includes a PV system linked to the utility grid and a local load via switches (S and S_1). The load, compliant with IEEE standards [91], is a parallel RLC load and is predominantly powered by the PV system, providing both active power (P_I) and reactive power (Q_I). Should there be a power deficit from the PV side, the utility grid injects the necessary power to compensate for the shortage, denoted as P_g and Q_g. Pg represents the difference between the active power required by the load and the active power supplied by the PV system. In contrast, Q_g signifies the difference between the demanded and provided reactive power by the PV system. Consequently, a bidirectional flow of electricity and information enhances the system's stability.

The following equations can describe the RLC active and reactive power demand:

$$P_L = \frac{V^2}{R} \tag{1}$$

$$Q_L = V^2 \left[\frac{1}{\omega L} - \omega C\right] \tag{2}$$

In an islanding situation, the utility grid circuit breaker (S_1) opens, isolating the rest of the grid and reducing both P_g and Q_g to zero. Subsequently, the local load relies solely on power from the PV system. The power imbalance between the PV system and the load, evident just before S_1 opens, defines the system's behaviour [92,93], indicating an islanding mode of operation.

If the active power of the load (P_L) is significantly larger than the PV system's output (P_I), the absence of P_g results in a decline in P_L. Consequently, the system responds by diminishing the RMS voltage at the PCC following Equation (1). On the other hand, if $P_L < P_I$, the load consumes what it requires, while the excess power flows to the utility system. Therefore, when S_1 opens, P_L is compelled to rise, increasing RMS voltage [94].

The reactive power imbalance is influenced by the reactive load component, with ΔQ being positive ($Q_L > Q_I$) for inductive loads and negative ($Q_L < Q_I$) for capacitive loads. In response to utility grid disconnection due to a reactive power imbalance, the system adjusts the frequency, meaning the voltage frequency at PCC (ω) will increase or decrease until Q_L equals Q_I in alignment with Equation (2) [41]. The PV inverter facilitates this adjustment, aiming to match the current-voltage phase angle of the load with that of the PV system [36].

The changes in voltage and frequency at the PCC can be monitored by protection relays, leading to islanding detection. The NDZ area can be calculated using active and reactive power imbalances, and frequency and voltage amplitude thresholds can be adjusted [95], as depicted in Fig. 3. The probability of ΔP and ΔQ, which the grid (P_g and Q_g) compensates for, lying within the NDZ can be considerable. Hence, over/under voltage and over/under frequency protection standards typically don't provide adequate anti-islanding protection alone and should be combined with other detection methods. Moreover, the NDZ depends on the type of load connected to the system, which is usually modelled as a parallel RLC circuit, as mentioned earlier.

4. Islanding detection methods

Island operation detection methods can be categorized into two main categories: active and passive strategies [96]. Passive

Table 1
The most common causes of unintentional islanding in PV systems include.

Observations	Causes
Loss of grid voltage or frequency	If the grid voltage or frequency falls outside the acceptable range, the photovoltaic system may continue operating, leading to unintentional islanding [77–79].
Faults in the distribution network	Faults in the distribution network can cause the photovoltaic system to become electrically isolated from the primary grid and lead to unintentional islanding [80–82].
Faults in the photovoltaic system	Faults in the photovoltaic system, such as a failure in the inverter or converter, can cause the system to become isolated from the primary grid and lead to unintentional islanding [83–85].
Transient voltage or frequency deviations	Transient voltage or frequency deviations in the electrical system can cause the photovoltaic system to become electrically isolated from the primary grid and lead to unintentional islanding [86–89].
Human failures, natural phenomena, and accidental opening of the distribution line caused by equipment failure. Intentional disconnection for services on the distribution line.	Lead to several system causes, including power quality and equipment damage [90].

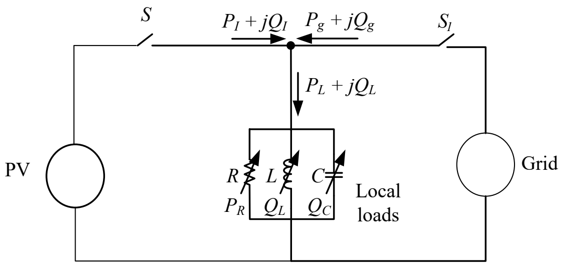

Fig. 2. Model of the distributed generation system for the study of islanding.

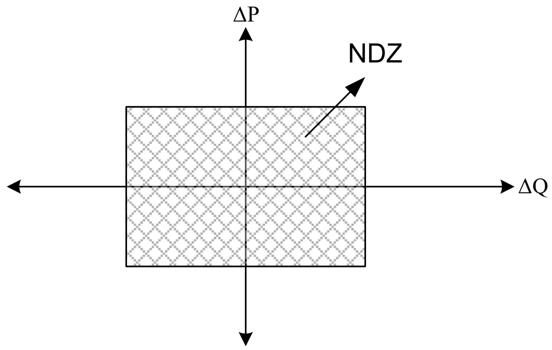

Fig. 3. An example of NDZ.

methods involve continuously monitoring the power grid parameters at the PCC, the interface between the DG system and the primary grid [97]. These parameters include magnitude, frequency, and phase. Passive methods can detect island operation by comparing these parameters to the values established by the IEEE 929 standard [98]. If the monitored parameters deviate from the standard values, it indicates the presence of an islanded operation, and the DG must disconnect from the grid [29]. The islanding detection methods require the fastest operation compared to the fast, automatic reclosing of the power system with a DG unit [99]. Fig. 4 presents a layout of islanding detection methodologies to apply in an innovative grid environment to operate microgrids effectively.

Passive methods for detecting island operation involve observing abnormal over or under voltages and over or under operating frequencies. The IEEE 929 standard specifies the parameters determining when the DG should disconnect from the PCC [97]. These parameters are defined in Tables 2 and 3 of the standard and express the frequency and voltage limits as a percentage of the PCC nominal voltage. By continuously monitoring these parameters and comparing them to the IEEE 929 standard limits, passive methods can effectively identify islanded operation and trigger the disconnection of the DG from the grid [100]. This disconnection is necessary to maintain the safety, stability, and reliability of the electrical system.

It is worth noting that active methods for island operation detection are also widely utilised [101]. These methods involve injecting specific signals into the grid and analysing the system response to detect any islanding condition. Active methods can provide additional means of detecting island operation, complementing the passive techniques [102]. Besides, active methods try to disturb the electrical parameters in the PCC. They can be classified into three subcategories: methods resident in the inverter, non-resident in the inverter, and methods based on communication between the system operator and the islanding detection system.

Fig. 5 shows a sketch of a grid-tied PV-based DG system consisting of several components. These components include:

- Array of panels: PV or solar panels that convert sunlight into electrical energy. The panels are typically connected in series or parallel configurations to provide the desired voltage and current levels.
- Converter: The converter, also known as an inverter, is responsible for converting the direct current (DC) power generated by the solar panels into alternating current (AC) power, which is compatible with the electrical grid. The inverter ensures that the power generated by the solar panels is synchronised with the grid's voltage and frequency.
- Local load: The local load represents the electrical appliances or devices connected to the DG system that locally consume the generated solar power. These loads include residential or commercial appliances, such as lights, refrigerators, and air conditioners.
- Distribution transformer: The transformer steps up or down the voltage levels between the DG system and the electrical grid. It helps match the voltage requirements of the DG system with the grid's voltage levels for efficient power transfer.
- Physical disconnect switch: This switch provides a physical means of disconnecting the DG system from the grid. It is used for maintenance or when the grid supply is interrupted, and the DG system needs to operate independently (island mode).

Passive strategies for islanding detection are commonly integrated into the inverter system, utilizing measurements of specific

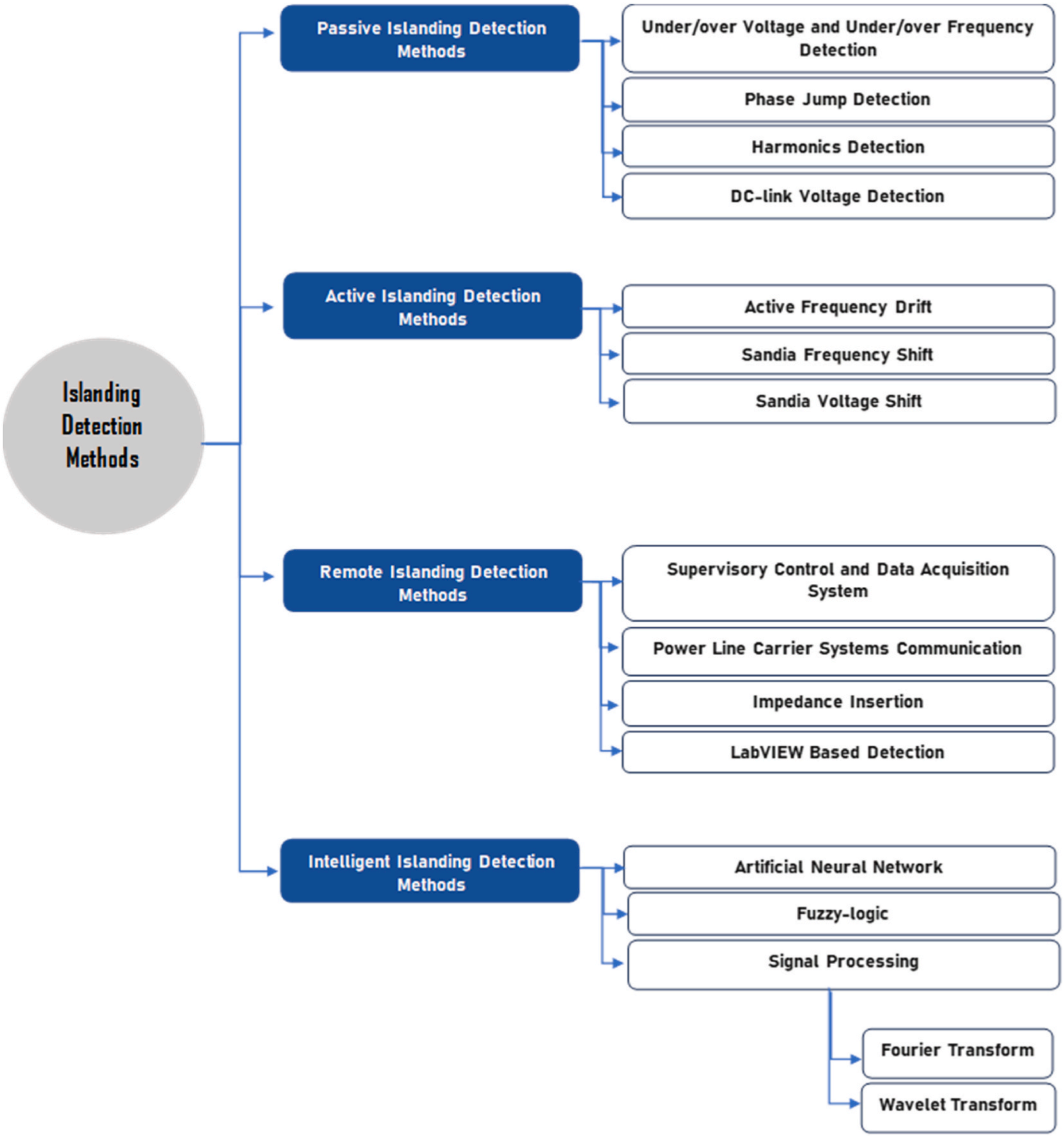

Fig. 4. Layout of Islanding Detection Methods is Smart Grid Applications.

Table 2
Response to abnormal frequencies (from IEEE Std. 929-2000).

Frequency (at PCC)	Maximum Trip Time	Maximum trip time in (ms) for 60 Hz systems
<59.3 HzFgrid <60.5 Hz	Normal Operation	Normal Operation
Fgrid <59.2 Hz	6 Cycles	100
Fgrid >60.6 Hz		100

Table 3
Response to abnormal voltages (from IEEE Std. 929-2000).

Voltage (at PCC)	Maximum Trip Time	Maximum trip time in (ms) for 60 Hz systems
(V < 50%)	6 cycles	100
(50% < V < 88%)	120 cycles	2000
(88% < V < 110%)	Normal Operation	Normal Operation
(110% < V<137%)	120 cycles	2000
(137% < V)	2 cycles	33.33

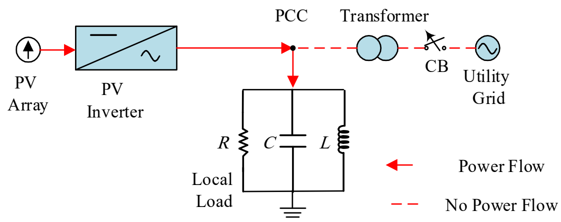

Fig. 5. System configuration for islanding study.

parameters such as voltage and frequency to identify an islanding situation. These approaches are less intricate and do not require supplemental grid interaction.

On the contrary, active detection methods may be executed within the grid or necessitate communication between the inverter and the grid. These methods engage more advanced techniques to proactively detect islanding occurrences, such as scrutinizing power flow, phase angles, or other grid parameters to establish whether the DG system is linked to the primary grid or functioning in isolation. Additional islanding detection strategies encompass remote islanding detection methods, signal processing-based detection techniques, and AI islanding detection approaches. Remote islanding detection methods can identify islanding incidents in intricate and

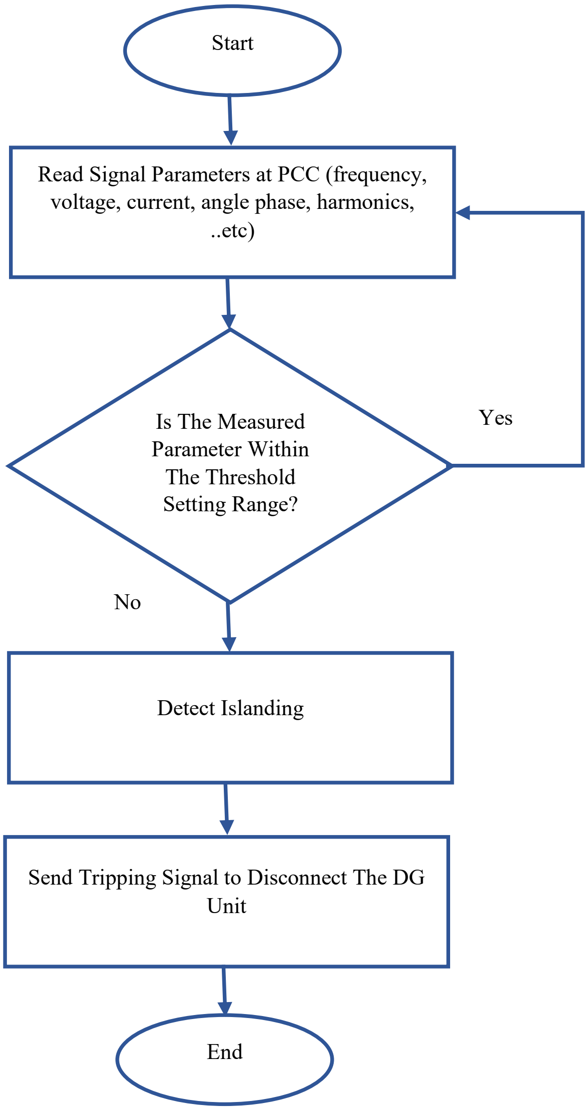

Fig. 6. Flowchart of passive islanding detection methods: a sample of working principle.

interconnected power systems where conventional local methods may be inadequate. However, they use communication technologies to transmit and analyze data, escalating system complexity.

Signal processing-based detection methods can deliver rapid detection and response to islanding incidents, enabling the timely disconnection of distributed generation units. These techniques predominantly rely on creating and deploying signal-processing algorithms to extract pertinent features and accurately detect islanding incidents. AI methods can acclimate to fluctuating system conditions and learn from new data, enabling enhanced detection performance over time. The following sections delve further into each islanding detection method.

4.1. Passive islanding detection methods

Passive islanding detection strategies operate by scrutinizing one or more parameters at the connection point of the distributed generator and the utility grid [103]. Observable variables include frequency, voltage magnitude, phase angle, and certain harmonic aspects or total harmonic distortion (THD). Notably, passive methods are praised for their capacity to preserve the power quality of electricity injected into the grid without causing any disturbances [104]. However, a significant drawback of these techniques is the substantial NDZ, which doesn't ensure islanding detection under all potential operating conditions [97]. For instance, passive methods include under/over voltage detection, under/over frequency detection, phase angle hopping detection, harmonic distortion detection [105], and DC-link voltage detection. Fig. 6 presents a flowchart of passive islanding detection techniques. This schematic gives a perspective of system design and modelling of estimation and control approaches to be developed for all islanding detection methods, as presented in Fig. 4.

4.1.1. Under/over voltage and under/over frequency detection

The over/under voltage (OUV) and over/under frequency (OUF) detection method represents a passive strategy for identifying islanding in distributed generation systems. It entails monitoring the voltage and frequency at the PCC, the connection interface between the distributed generator and the utility grid [106]. The acquired voltage and frequency readings are then contrasted with established upper and lower thresholds dictated by regulatory standards. By juxtaposing the measured values with these predefined limits, this method can flag potential islanding events if any of the monitored parameters deviate from the permissible range [91]. Suppose the voltage or frequency exceeds the upper or falls below the lower limit; it implies that the distributed generator could be operating in an island mode, disconnected from the main grid.

The OUV and OUF methods are commonly employed via software algorithms integrated into the control system of the distributed generator, particularly within photovoltaic inverters. Beyond detecting islanding events, this method also protects the photovoltaic inverters, shielding them from damage due to under/overvoltage or frequency fluctuations in the grid [107]. The benefits of the OUV and OUF methods are consistent with those of passive techniques, and some key advantages of this strategy are highlighted in Table 4.

It is crucial to underscore that while the OUV and OUF techniques provide simplicity and cost-effectiveness, they also inherit a fundamental limitation typical of passive methods: the NDZ. The NDZ represents operational conditions under which the method might fail to detect islanding events reliably. This strategy suffers from a considerable NDZ, hindering islanding detection during minor variations. The worst-case scenario for islanding detection occurs when there is a balance between the active and reactive power, causing the amplitude and frequency to remain constant. This state is defined by Equations (3) and (4) for the minimal values of grid active power (ΔP) and grid reactive power (ΔQ), respectively [106]. These equations define the NDZ for both active and reactive power. The accuracy of islanding detection can be improved, and this limitation can be mitigated by integrating passive and active methods or adopting advanced techniques.

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

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

4.1.2. Phase jump detection

This approach hinges on tracking the phase discrepancy between the inverter's output current and the voltage available at the PCC. The detection of a grid interruption discerns an immediate phase difference between these two variables. For inverters operating as a current source, a phase-locked loop (PLL) maintains the synchronization between the inverter and the grid in a non-island operation, leveraging the grid's ability to offer a stable voltage reference [41,108].

Table 4
Key advantages of passive technique: OUV and OUF.

Features	Descriptions
Simplicity	The method is relatively straightforward and does not require complex hardware components. Instead, it relies on software algorithms to monitor and compare voltage and frequency values.
Low cost	Since it can be implemented through software, the additional cost associated with specialized hardware is minimal, making it an affordable solution for islanding detection.
Non-degradation of energy quality	The OUV and OUF strategies maintain the quality of the energy fed into the electrical grid without compromising it. It supervises voltage and frequency without actively influencing the power output.

Upon grid disconnection, the interaction between the output current and the load impedance shapes the voltage at the PCC. The current remains consistent and aligned with the sinusoidal reference provided by the PLL. As the PLL dictates synchronism at the zero-crossings of the voltage waveform, any network disruption outside the crossing region will prompt changes in the PCC voltage to align with the phase angle of the local loads [109].

A vital advantage of this method is its minimal computational load on the inverter code, given its implementation alongside the PLL. As a passive method, it also avoids any degradation in energy quality. Moreover, it's noteworthy that there's no loss in detection efficiency in multi-inverter situations.

The principal drawback of the phase jump detection scheme is the selection of a dependable threshold for permitted phase jumps [40]. A narrower threshold allows for improved detection with a smaller NDZ. Still, it may result in inappropriate inverter shutdowns as phase jumps can occur during standard operational circumstances, like the activation of motors [41]. Conversely, a more lenient threshold leads to a larger NDZ.

4.1.3. Harmonics detection

This method identifies islanding by observing harmonic distortion in the voltage at the connection point between the PV system and the electrical grid [41]. Under standard operating conditions, the inverter directs most harmonic currents towards the power grid when islanding is absent. This directionality is due to the electrical system's impedance being comparatively lower than that of the load. In such scenarios, the passage of harmonic currents through the electrical system results in minor harmonic distortions in the grid voltage. However, upon disconnection from the utility grid, the inverter's currents must traverse the high impedances of the loads, resulting in substantial harmonic voltages. This surge in harmonic voltage initiates the islanding protection mechanisms [110].

Although this technique is easy to implement and causes little interference in the quality of electrical energy, its use is not very commercially viable due to the difficulty in adjusting the voltage distortion levels so that it is considered islanding, not to mention that some voltage disturbances, such as capacitor bank switching transients, can cause unnecessary disconnections.

4.1.4. DC-link voltage detection

In PV systems, the voltage generated by the photovoltaic effect fluctuates due to radiation and temperature factors, increasing the demand for a DC-DC converter that delivers constant voltage. The DC-DC converter steps up the produced voltage to an extent that is compatible with the system, and the output voltage is the DC-link voltage (V_{dc}) [111]. To maintain the voltage constant, the measured voltage at the DC link is compared to the reference value, which is usually set as 900 V, and the difference determines the duty cycle (k) of the PWM signal [111,112]. V_{dc} is infused into the inverter as the input, and its value is determined by the peak value of the required AC voltage output; thus, any variation in the V_{PCC} will cause V_{dc} to change whereby it adopts the changes [112].

DC-link voltage detection method counts on the fact that during a grid-connected system, and assuming losses are neglected, the total amount of power generated by PV is injected into the grid, yielding the following relationship:

$$P_{PV} = P_G = 3V_{Grms}I_{Grms} \tag{5}$$

Where P_{PV} is PV-generated power, P_G is the grid power, and V_{Grms} and I_{Grms} are the RMS phase voltage and RMS phase current, respectively. However, when islanding occurs and voltage at PCC is sagging, Equation (5) is violated owing to the alleviation of active power accompanying the voltage reduction. It's worth noting that the DC-DC converter continues to operate, striving to extract maximum power from the PV system and transfer it to the grid. Hence, any excess energy from the PV system increases C-link power, which correlates with the power imbalance [113]. The threshold settings can be determined by simulation where the value of V_{dc} prior to opening the circuit breaker and afterwards are compared considering various load values. The results reveal that this method fails to detect the islanding phenomenon for a power mismatch between −20% and +20% [114]. However, it successfully detects islanding and fire trip signals in a concise duration of up to 0.02 s.

4.2. Active islanding detection methods

Active methods operate based on the principle of regularly injecting a minor disturbance signal into the grid, which prompts parameter changes at the PCC and causes them to exceed threshold settings solely in the event of islanding. Active methods can be

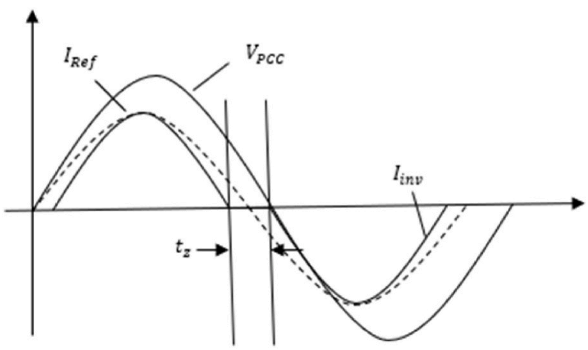

Fig. 7. PCC Voltage waveform and inverter current compared to reference current.

categorized into two types based on the origin of the action: local active methods, wherein the inverter system dispenses the disturbance signal, and remote active methods, which are governed by the primary grid side [115]. Consequently, the PV inverter output current can be expressed by Equation (6). The active islanding detection methods use the flowchart of Fig. 6.

$$I_{inv} = I_m \sin(2\pi \text{ f t} + \theta) \tag{6}$$

where f is the frequency, I_m is the inverter current amplitude, and θ is the initial phase angle. The disturbance signal can alter these parameters, and according to the methods of adding the disturbance and which parameters are affected, several active detecting methods are introduced in studies.

4.2.1. Active frequency drift

Active frequency drift (AFD) is an active method in the inverter system. The reference current is distorted due to the disturbance signal that changes the current frequency by producing a chopping part.

In the standard AFD, shown in Fig. 7, the injected signal causes the frequency of the inverter output current to be a bit higher than the utility grid frequency, and it introduces a zero-conduction time, t_z in the first half-cycle. The second half-cycle of the inverter output current is a negative extension of the first half-cycle. Yet, the zero-conduction time is not equal to that of the first half-cycle as it lasts until the rising edge of the grid voltage [116]. In islanding mode, the voltage waveform attempts to follow the inverter output current to maintain the unity power factor. This results in phase error as the voltage-raising edge appears sooner than expected. The frequency of the voltage waveform will increase in response to the phase error to match the load's resonant frequency, and protection devices will recognise the frequency drift. The ratio of zero-conduction time, t_z, to the half of the utility grid voltage period is the chopping factor, cf.

$$cf = \frac{2t_z}{T} \tag{7}$$

The chopping factor is a fixed value; the more significant the chopping factor, the narrower NDZ. However, the regular injection of significantly distorted waveform adds to the THD, reducing system efficiency [117]. Therefore, many improved AFD methods were presented in the literature [90,118].

4.2.2. Sandia frequency shift

The Sandia frequency shift (SFS) represents an improved variant of the active frequency drift method, often referred to as active frequency drift positive feedback (AFDPF) [119]. The concept of SFS is similar to AFD, where the inverter current distortion happens through injecting zero-conduction time, t_z, which creates phase misalignment that effects the waveform frequency. However, the use of positive feedback in SFS aids in accelerating the frequency drift from the threshold operating values, which results in shorter islanding detection time [120]. Unlike AFD, the chopping factor, cf varies depending on the amount of frequency drift [121]. cf of SFS is given as:

$$cf = cf_o + k(f - f_n) \tag{8}$$

Where cf is the chopping factor, cf_o is the inherent chopping factor, k is the positive feedback gain, f is the measured frequency at PCC, and f_n is the nominal grid frequency. In normal operating mode, the cf is constant and equals to cf_o. When islanding occurs, cf increases because of the emergence of a frequency shift and the frequency change is determined by the value of k.

The optimal parameter design is a critical factor in the efficiency of the SFS method. Therefore, to eliminate the NDZ, a mathematical approach is developed to calculate the best SFS islanding detection parameter setting [122].

4.2.3. Sandia voltage shift

Sandia voltage shift method employs positive feedback of voltage amplitude at PCC to detect islanding. It is considered the most viable technique among the other positive feedback-dependent methods [121,123]. In islanding mode, the utility grid is no longer a solid voltage supply, and the voltage at PCC will fluctuate according to the PV inverter output current. V_{PCC} describes the voltage at PCC, and it is represented as follows:

$$V_{PCC} = V_{inv} = I_{inv} Z_{load} \tag{9}$$

Thus, the active power can be written as:

$$P_{load} = P_{inv} = \frac{{V_{PCC}}^2}{R} \tag{10}$$

Since the voltage at the PCC is directly proportional to the PV inverter current output, as formulated in Equation (9), an increase in PCC voltage increases the current injected by PV to the grid, increasing the active power. The increment in the active power causes a further increment in the voltage at PCC, and this process continues until the OV relay trips. Similarly, decreasing PCC voltage will eventually cause the UV relay to trip. To create the positive feedback in the Sandia voltage shift method, a disturbance current is added to the PV system and can be expressed as [117]:

$$I_{dis} = kV_e \tag{11}$$

Where k is the feedback gain that increases or decreases the inverter output current when there is a variation in voltage to enhance the detection speed and V_e is the error which resembles the difference between the detected voltage at PCC and the nominal voltage.

Like the other active detection methods, Sandia voltage shift adds to the total harmonic distortion. However, it has a very small non-detectable zone [124].

4.3. Remote islanding detection methods

Remote islanding detection methodologies employ communication frameworks that facilitate information exchange among the DG, protective mechanisms, and utility. They trigger anti-islanding safeguards using data and parameters from the utility. These techniques are characterised by high reliability, an absence of NDZs, faster response times, zero detrimental impact on power quality, and effective operation across various DG systems. However, they are more expensive and necessitate a rapid, reliable communication system.

4.3.1. Supervisory control and data acquisition system

Supervisory control and data acquisition (SCADA) is a system capable of collecting data from a remote terminal unit (RTU) [125] or programmable logic controllers (PLC), equipment where the sensors are connected, and displaying them in real-time in an intelligible way on a human-machine interface. This system offers three essential functions: supervision, operation and control of the collected data.

- Supervision: Allows monitoring of acquired data.
- Operation: Allows you to send commands to equipment in the field.
- Control: Can act automatically in certain situations.

SCADA is the name given to the entire system that acquires data in the field, supervises them and allows the operator to control or make decisions based on the value [126].

4.3.2. Power line carrier systems communication

Power line carrier systems communication uses the existing structure of electrical system lines as a communication channel to monitor signals continuously transmitted from distribution feeders to distributed generators equipped with receivers [127]. If the signal is interrupted at any point in the system, not sensitising the receivers installed in the distributed generators, islanding will be identified [40]. In this case, the same implications are not discussed for SCADA systems regarding changes in the structure of the electrical system, as they depend only on the communication link between the distributed generators and the concessionaire. Although a highly reliable technique, the system may disconnect improperly distributed generators if the grid voltage signal is interrupted.

4.3.3. Impedance insertion

The impedance insertion technique incorporates a minute impedance value when islanding occurs in the DG. The introduction of a capacitor aids in managing reactive power, thereby influencing the power equilibrium between generation and load. Subsequently, the reactive power from the capacitor bank impacts the voltage and frequency. The islanding detection frequency relay in the primary grid can then identify the induced frequency distortion, thereby detecting islanding [41].

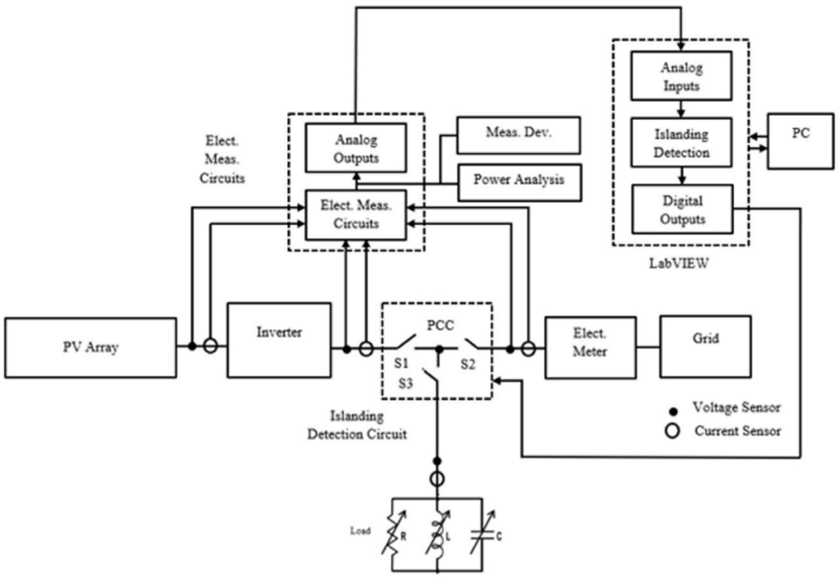

Fig. 8. System Structure of LabView-based method.

4.3.4. LabVIEW based detection

Unlike most anti-islanding methods, this method continuously observes changes in the grid, PV, and load sides. This technique has an advantage over other islanding detection techniques that measure only parameters at the point of common coupling, which raises NDZ issues as they are load-dependent. The system consists of three circuit breakers (load CB, grid CB, and PV CB), electric measurement instruments, and the LabVIEW-based controller, as shown in Fig. 8 [128].

This islanding detection technique initially checks the current of the circuit breakers and determines the occurrence of islanding once any of them declines to zero. It also detects islanding if these currents are off threshold limits.

The benefit of this method, besides eliminating NDZ, is the low cost, as there is no need for additional telecommunication instruments. Furthermore, it has high reliability as it does not only monitor the CBs currents nor PCC voltage but other parameters (like current, frequency, active and reactive power), which are fed to the analog inputs to the Digital/Analog converter of the LabVIEW to be analysed and in case of islanding, CB control signals will be generated.

4.4. Intelligent islanding detection methods

Intelligent techniques, such as AI-based islanding detection methods, possess high reliability and precision. These methods are based on creating a database that trains the classifier to recognise the islanding mode of operation. The database consists of possible islanding conditions and instructions to help with the decision-making process. The classifier then analyses the current input signals and decides whether the system operates under normal or islanded operation settings. As such, AI methods mimic human beings' cognitive ability to make judgments based on the available information, except they are faster [129]. These strategies use soft-computing methodologies to control the PV system and guarantee the smooth transfer of microgrids based on the flowchart modelling for the system algorithm, as presented in Fig. 6. In [130], a novel soft-computing approach-based adaptive neuro-fuzzy inference system for inverter-interfaced microgrids is proposed to handle the islanding detection. The developed strategy is evaluated within different load conditions. Thus, the soft-computing environment provides an accurate, authentic, practical, precise and selective power quality with minimisation of THD.

The AI method brings several soft computing techniques for islanding detection methods in the innovative grid environment under different applications. In [131], support vector machine, one of the machine learning (ML) strategies, is developed for active distribution network with DG for accurate fault and islanding detection of microgrid. The approach guarantees the accuracy and reliability of the grid-tied inverter-interfaced microgrid based on a PV system. In [132], a support vector machine based on the passive method coordinates anti-islanding protection of grid-tied PV with plug-in hybrid electric vehicles. It is observed that employing the developed strategy makes it possible to monitor several variables to ensure the power quality of the microgrid. Therefore, the stability of the system voltage is effectively guaranteed when intelligent techniques can handle the dynamic behaviour of the passive islanding detection method.

4.4.1. Artificial Neural Network

Artificial neural network (ANN) applications employ deep learning to adopt solutions for problems that methods based on setting rules are unable to solve. Furthermore, ANN can recognise patterns in the fed signals, a characteristic that becomes handy when determining the island. Therefore, it is essential to select the suitable ANN architecture alongside the training set to guarantee the accuracy of results.

The most popular network design in anti-islanding applications comprises inner, hidden, and outer layers. Firstly, the input data is transformed into a simple form to process and fed to the inner layer. Then, each input will be assigned a weight given randomly at the beginning and altered later when necessary. The summation of each input times its corresponding weight will be calculated. The neurons which form the layers are responsible for these calculations and driving the output [133].

Voltage waveform samples are obtained using the moving data window (MDW) to train ANN for islanding detection. These samples, which represent the voltage measurements under different operations, are translated into vectors and passed to the inner layer for processing. Results are obtained, which may be high in case the utility grid is disconnected or low when connected [134]. Then, the validity of the results is evaluated by histograms and performance curves [135].

This AI method is flexible when the expected output by ANN does not match the obtained result when the backpropagation testing process can be used to readjust the predefined weights, consequently reducing the error. However, the training procedures may be time-consuming and difficult.

4.4.2. Fuzzy-logic

The architecture of a fuzzy-logic network consists of fuzzier, intelligence, de-fuzzier and rules defined by experts. The Fuzzier is responsible for converting the input, which can involve voltage, rate of change of frequency, and rate of change of active power measurements [136], into a fuzzy set that will be passed to the intelligence. Intelligence is where the decision-making takes place; it compares the fuzzy input set with the predefined rules, which are if-else rules and measures the matching level. Finally, the fuzzy output set is generated and passed to the de-Fuzzier to interpret it into normal control signals. The advantage of fuzzy is its ability to model a control strategy combined with various soft-computing methods, such as a neuro network, to guarantee the protection of interconnection and stabilisation of microgrids [130].

The highlighted advantage of fuzzy-logic networks is the easy implementation as it can describe the relationship between non-linear input and output with the help of simple logic rules and doesn't require the utilisation of complex devices, making this method affordable. Additionally, fuzzy-logic anti-islanding methods may experience a lack of accuracy since they can work with imprecise input. Besides, it is heavily dependent on humans; therefore, it is prone to counter human faults. Moreover, fuzzy-logic networks lack self-learning ability; thus, constant development may be required. In literature, a neuro-fuzzy system is proposed to benefit from both methods advantages [137].

4.4.3. Signal processing

Signal processing methods are characterised by high stability and versatility [138]. Signals are analysed in the islanding detection scope, and disturbances are identified. Then, these disturbances are compared with threshold values to determine islanding occurrence. Skewness, kurtosis, and energy of each oscillatory level are among the signal characteristics of signal processing methods examined [139].

Signal processing techniques are usually utilised alongside passive islanding methods to minimise their large NDZ. Another common application for signal processing methods is to be used as a former stage for artificial intelligent detection methods to extract the required features for the classifiers.

4.4.3.1. Fourier Transform. Fourier transform (FT) is the mathematical representation of a signal in the frequency domain from its time domain. It is the summation of sine and cosine components of signals whose frequencies do not alter with time [140,141]. Therefore, FT is incapable of analysing the fluctuated signals attributable to islanding; besides, time-frequency analysis is needed, namely, short-time Fourier transform (STFT) [141].

STFT divides a time-domain signal into a sequence of small segments and considers each component stationary. Most of the conventional STFT applications are conducted using fast fourier transform (FFT). FFT is designed to compute the discrete Fourier transform (DFT) of discrete signals. It minimises the complexity and the processing speed of DFT. Hence, FFT is preferable in detecting islanding.

Fourier transform is affordable for islanding detection due to its high efficiency and robust results. Moreover, it can modify the conventional harmonic detection passive method discussed earlier, as it has a smaller NDZ than the traditional method [142]. Yet the analysis in FT depends on the resolution, defined as the minimum alteration that is detectable. The resolution, in turn, depends on the selected window fixed in FT. Therefore, FT cannot be used for all frequencies.

4.4.3.2. Wavelet Transform. Wavelet transform (WT) provides time localisation, showing when a particular event occurs. It also indicates the way frequency content varies over time. These characteristics make WT suitable for islanding detection since the required time-frequency analysis is provided. Similarly to FT, WT projects a time-domain signal in the frequency spectrum [143]. However, it can examine signals at different frequencies, making it ideal for detecting the fast transients that feature signals changing in case of islanding. This ability stems from the adaptive window that WT uses.

WT breaks down a signal into wavelets [138]. Each wavelet is an oscillation that looks like a wave characterised by two components: scale and location. The scale describes how much a wavelet is stretched or contracted; in other words, it represents the frequency of the wavelet. Location determines the wavelet's position in time. The wavelet shrinks in high-frequency duration yet expands in low-frequency period automatically, which allows the wavelet to capture the frequency information of a signal [144].

WT can be used to detect islanding in both synchronous-based DGs and inverter-based DGs. Generally, it has high flexibility, accuracy, and reliability. However, it is worth noting that the performance of WT as an anti-islanding algorithm essentially relies upon the choice of the mother wavelet, and the best selections are db4 and db8 [144].

5. Discussion and scope for future works

As presented in Sections 3-4, from the comparison between the active and passive islanding detection methods, active techniques inject disturbances into the electrical network and degrade energy quality. The combination of different islanding detection methods, such as active and passive techniques, assists in adequate power quality and THD reduction of the grid-tied PV system [145]. It was confirmed that the SFS technique was more aggressive for THD, voltage and frequency deviation than the AFD technique. Additionally, these disturbances injected into the network facilitate island detection and reduce the NDZ. However, it is essential to emphasise that the NDZ depends not only on the active technique but on numerous parameters such as different DG controls, the type of load, the protection relay actuation time, and the power factor.

In particular, in active islanding methods, it is vital to choose the amplitude and frequency of the disturbance to guarantee the detection of the disruption in the island and, at the same time, not to affect the quality of the local voltage. There was a need to introduce a delay time for islanding confirmation and, thus, discriminate from other possible voltage disturbances at the common

Table 5
Advantages of innovative grid technology in islanded detection of PV systems.

Features	Description	Refs.
Real-time Monitoring	Innovative grid technologies enable real-time monitoring of the electrical grid and PV systems. This allows for immediate detection of islanding events and quicker response times to mitigate potential risks.	[146–148]
Communication and Control	Intelligent grid systems facilitate communication and control between PV systems and grid infrastructure. This enables active islanding detection techniques that involve actively injecting signals or manipulating system parameters to monitor grid behaviour.	[149–152]
Data Analysis and Decision Support	Smart grid technologies enable the collecting, analysing, and processing large amounts of data from PV systems and grid components. This data can be used to develop advanced algorithms and decision support systems for improved islanding detection accuracy.	[153–155]
Grid Stability and Resiliency	Smart grid applications enhance grid stability and resiliency by detecting and preventing islanding conditions. This ensures the safety of utility workers and protects equipment from damage during grid maintenance or repair.	[156–158]

coupling point, such as those generated by load transients.

The incorporation of advanced grid technologies is paramount for the seamless and efficient integration of solar PV systems into the electricity grid. A vital component of this integration pertains to detecting islanding scenarios where a PV system continues to power a local grid even when the primary grid is disconnected. This article systematically reviews and examines various islanding detection methods specifically designed for solar PV systems. This comprehensive evaluation measures the efficiency, reliability, and performance of different islanding detection techniques applicable to PV systems. The adoption of innovative grid technologies concerning islanding detection methodologies for solar PV systems offers numerous advantages. Thus, Table 5 provides more features and descriptions of innovative grid technology in the islanded detection of PV systems.

The critical assessment of islanding detection methods for solar PV systems provides valuable insights into the strengths and limitations of different techniques. Furthermore, integrating smart grid technologies in this context helps enhance the reliability and effectiveness of islanding detection, thereby promoting the successful integration of solar PV systems into the electrical grid. Besides, Table 5 provides intelligent grid applications involving in-depth discussions and analysis of the various techniques for detecting islanding conditions. Therefore, some potential highlights of this critical assessment can be described as follows:

1. Comparative Analysis: The assessment may involve a comparative analysis of different islanding detection methods, such as passive, active, and remote techniques. The discussions could focus on their principles of operation, reliability, sensitivity, false-positive/negative rates, and overall performance.
2. Performance Evaluation: The assessment may evaluate the performance of each detection method based on different criteria. These criteria may include response time, accuracy, robustness against system dynamics, adaptability to different PV system sizes or configurations, and effectiveness in various grid conditions.
3. Technology Advancements: Discussions could revolve around recent technological advancements in islanding detection methods within the context of innovative grid applications. This may include using advanced signal processing techniques, machine learning algorithms, or advanced communication protocols to enhance the accuracy and reliability of islanding detection.
4. Communication and Control: The assessment may investigate the importance of communication and control mechanisms within intelligent grid applications for effective islanding detection. The discussions could explore the role of communication protocols, data exchange formats, and control signals in facilitating real-time monitoring, system coordination, and accurate islanding detection.
5. Grid Integration Challenges: The discussions could address the challenges associated with integrating solar PV systems into the electrical grid and how they impact islanding detection methods. Topics such as grid stability, synchronization, system protection coordination, and interaction with other distributed energy resources may be explored.
6. Field Testing and Validation: The assessment may discuss the importance of field testing and validation of islanding detection methods. The discussions could focus on the significance of real-world scenarios, different test configurations, and guarantee against standard test procedures or grid codes to ensure the reliability and effectiveness of the detection methods.
7. Standardisation and Regulations: Discussions could address the need for standardisation and regulatory frameworks governing islanding detection methods in innovative grid applications. This may include examining existing standards and regulations, identifying gaps, and proposing recommendations for standardisation bodies and policymakers.

The critical assessment would comprehensively understand the strengths, limitations, and advancements in islanding detection methods for solar PV systems within innovative grid applications. It would also highlight areas for further research and development to improve the overall reliability and performance of islanding detection techniques. The future direction can also look at the stability operation of the power inverter in terms of their protection to guarantee the system performance of microgrids.

The innovative grid technologies provide several features for fast monitoring and control of microgrids with various energy storage systems [66]. Table 5 provides the advantage of applying the innovative grid technology in islanding detection methods. Thus, the future scope can be summarized as follows:

- Apply the feature of innovative grid technologies with two-way communication between diverse components of the power network to guarantee a predictive and autonomous islanding detection of the grid-tied PV system. This system requires effective monitoring based on real-time state estimation for various microgrid control variables. The software computing strategies also offer the opportunities to coordinate different islanding detection methods.
- The innovative control approaches based on intelligent control techniques offer opportunities for identifying detection methodologies in different operating mode microgrids with DGs. Therefore, softcomputing approaches are the most promising methods based on intelligent control techniques for effective islanding detection strategies.

6. Conclusion

This article discusses various techniques for detecting islanding conditions, categorized into passive, active, and remote methods. Islanding refers to a situation where a distributed power generation system, such as a PV system, continues to supply power to a local electrical grid despite a grid failure. Passive islanding detection techniques rely on monitoring changes in system parameters or power quality during islanding. However, these methods may have limited reliability, as they may fail to detect islanding when the load consumes all the power generated by the PV system. Therefore, the passive techniques may not meet the minimum requirements for adequate anti-islanding protection in such cases. Besides, active islanding detection techniques are known for successfully detecting islanding conditions. These methods involve actively injecting signals or manipulating system parameters to monitor grid behaviour changes. These techniques can effectively differentiate between grid-connected and islanded operations by actively perturbing the system. As mentioned in the article, remote methods likely focus on monitoring the system remotely. These techniques may involve communication between the distributed power generation system and a central control centre, allowing real-time monitoring and detection of islanding events. It is essential to ensure reliable islanding detection to protect the safety of utility workers and prevent damage to equipment during grid maintenance or repair. Active techniques are generally considered more robust in detecting islanding conditions than passive strategies, as they actively interact with the system to monitor its behaviour.

As we venture into the 21st century, the demand for reliable and efficient integration of solar photovoltaic systems into our power grids continues to increase. With this trend, the need for advanced islanding detection techniques becomes increasingly critical. In the future, we anticipate significant developments in several areas of islanding detection. AI and ML methods are emerging as powerful tools for islanding detection. These techniques can adapt to changing grid conditions and learn from new data, allowing for improved detection performance over time. AI and ML can provide a more nuanced understanding of system behaviour, potentially identifying islanding situations that other methods may miss.

Declaration of competing interest

The author declares that there are no financial or personal relationships with other people or organizations that could inappropriately influence (bias) this work. There is no professional affiliation or involvement within a commercial organization possessing a direct financial interest in the subject matter or materials discussed in the manuscript (e.g., employment, consultancies, stock ownership, honoraria, expert testimony). The author does not have any patent applications or grants pending. Any other interests that could appear to influence the work reported in this paper, such as personal or professional relationships, affiliations, knowledge or beliefs are not present.

The authors are solely responsible for the content and writing of the paper. All research and ethical guidelines have been followed as required for the conduct of scientific research.

Data availability

No data was used for the research described in the article.

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