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Article

# Islanding Detection Techniques for Grid-Connected Microgrids and a Proposed Frequency–Reactive Power Hybrid Framework.

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**Abstract:** The increasing penetration of distributed generation (DG) based on renewable energy sources is transforming passive radial distribution networks into active, bidirectional microgrids. While this transition improves efficiency, reliability and environmental performance, it introduces the risk of unintentional islanding, whereby a DG unit continues to energize part of the network after the utility grid has been disconnected. Undetected islanding endangers maintenance personnel, can damage connected equipment, and disrupts protection coordination and power quality. Over the past two decades, researchers have proposed remote (communication-based), active, passive and hybrid islanding detection methods (IDMs), each involving trade-offs among the non-detection zone (NDZ), detection speed, power-quality impact, cost and robustness under multiple parallel-connected inverters. This paper organizes and critically compares these techniques with reference to the IEEE 1547 and UL 1741 anti-islanding requirements, and identifies two recurring limitations: the unreliable operation of passive schemes near zero power mismatch, and the continuous power-quality penalty imposed by active perturbation. Motivated by these gaps, a hybrid islanding detection framework is proposed that jointly monitors the frequency response of the point of common coupling (PCC) to a small, closed-loop reactive-power perturbation at the inverter output, with the perturbation gain increased through positive feedback once a passive stage first flags a suspected island. The proposed control architecture, detection algorithm, and a three-stage MATLAB/Simulink-based validation methodology, referenced against IEEE 1547 and UL 1741, are described.
**Keywords:** Distributed generation, hybrid islanding detection, microgrid protection, non-detection zone, passive islanding detection, point of common coupling, reactive power control, renewable energy

## 1. INTRODUCTION

Electricity demand continues to rise worldwide, and with it the expectation that supply be more reliable, efficient, environmentally sustainable and cost-effective than the conventional model of one-directional bulk power flow from centralized generating stations. Distributed generation (DG) — small generating units connected at the distribution level, most commonly photovoltaic, wind, fuel-cell and mini-hydro sources — addresses these expectations by enabling bidirectional power flow and by locating generation closer to load. The aggregation of DG units, storage and controllable loads operating under coordinated control is generally referred to as a microgrid, and the accelerating deployment of microgrids is a central feature of the ongoing transition toward smart distribution networks.

High penetration of DG, however, introduces a set of operational challenges at the distribution level, including voltage rise, reverse power flow, power-factor deviation, voltage and power fluctuation, frequency deviation, harmonic injection and, of particular concern to protection engineers, unintentional islanding [30]. Islanding occurs when a section of the distribution network — comprising one or more DG units and their local loads — becomes electrically isolated from the main utility grid, most often due to a fault, a protective trip, a scheduled switching operation, or an equipment failure, while the DG units continue to energize that section autonomously. Because most DG technologies deployed today are power-electronic-interfaced (inverter-based) and lack the inherent inertia and fault-current characteristics of synchronous generation, an undetected island can drift in voltage magnitude and frequency well outside the bounds tolerated by connected equipment, risk out-of-synchronism reclosure by the utility, and — most critically — endanger the safety of line crews who reasonably assume a de-energized feeder during maintenance.

These consequences have made islanding detection a long-standing and still-active research area. The methods proposed in the literature are broadly grouped into remote (communication-based) methods, which rely on continuous communication between the DG and the utility to signal a breaker operation, and local methods, which infer islanding from measurements taken at or near the DG terminals without dedicated communication infrastructure. Local methods are further divided into active methods, which deliberately inject a small disturbance into the system and observe the response, and passive methods, which monitor system variables such as voltage, frequency, harmonic content or phase for a deviation characteristic of islanding [25]. A fourth category, hybrid methods, was subsequently developed to combine active and passive criteria in an effort to retain the low non-detection zone (NDZ) of active schemes while avoiding their continuous power-quality penalty.

Despite this large body of work, no single method has emerged as universally applicable: the reported techniques differ in their DG-technology dependence, their behaviour when multiple inverters operate in parallel, their sensitivity to the power mismatch between generation and local load at the instant of islanding, and their compliance margin against standards such as IEEE 1547 and UL 1741 [23]. The remainder of this paper is organized as follows. Section II describes the islanding phenomenon and the consequences of failing to detect it. Section III presents a taxonomy of islanding detection methods. Sections IV–VI review remote, active/passive local, and hybrid methods, respectively. Section VII compares the reviewed families of methods qualitatively. Section VIII discusses reliability considerations specific to islanding-capable microgrids. Section IX states the research gap motivating this work. Section X proposes a hybrid frequency–reactive-power islanding detection framework, and Section XI outlines the simulation-based methodology that will be used for its validation. Section XII concludes the paper.

## 2. THE ISLANDING PHENOMENON: CAUSES AND CONSEQUENCES

An islanding event can originate from a planned action, such as a scheduled feeder-switching operation, or from an unplanned one, such as a fault followed by protective isolation, an equipment failure, or accidental conductor damage. In either case, if the isolated section contains DG capacity comparable to its local load, the DG units may continue to energize that section without any indication, at the DG terminals, that the connection to the main grid has been lost.

The consequences of an undetected island are threefold. First, because the DG no longer receives the voltage and frequency reference of the bulk grid, the islanded section's voltage and frequency are governed solely by the local generation–load balance and by the DG's own control loops; both quantities can drift outside equipment ratings and degrade power quality [23]. Second, an islanded section reconnected to the grid without verifying phase, voltage and frequency synchronism can subject the DG, the local loads and the wider network to large transient currents and torques. Third, and most critical from a safety standpoint, personnel dispatched to service what is assumed to be a de-energized feeder may instead encounter a live conductor, since conventional substation protection cannot, by itself, distinguish a genuinely de-energized feeder from an islanded one.

It is useful to distinguish this unintentional-islanding problem from controlled (intentional) islanding, in which a large-scale power system is deliberately split into self-sufficient sub-systems during a severe disturbance in order to arrest cascading outages [27]. The protection and detection requirements of the two problems differ substantially: controlled islanding is a planned, system-level response to instability, whereas the unintentional islanding addressed in this review must be detected reliably at the level of an individual DG unit or feeder, typically within a few hundred milliseconds, under otherwise normal operating conditions.

A further complication is that reported islanding detection methods are frequently validated for a single dominant DG technology, most often inverter-interfaced photovoltaic generation. Because a method's detection principle and NDZ depend on the DG's electrical characteristics, a technique shown to perform well for one DG type may fail, or require re-tuning, when applied to a feeder hosting a heterogeneous mix of DG technologies or multiple DG units operating in parallel. Designing an islanding detection approach that is both accurate and largely DG-type-agnostic therefore remains an open problem, and is a central motivation for the present work.

## 3. TAXONOMY OF ISLANDING DETECTION METHODS

Fig. 1 summarizes the classification adopted in this review. Islanding detection methods (IDMs) are first divided into remote (communication-based) and local methods. Local methods are further divided into active methods, which inject a disturbance and monitor the resulting deviation, and passive methods, which monitor existing system variables against a threshold without injecting any disturbance. Hybrid methods combine elements of both categories, typically arming an active perturbation — or treating it as confirmatory evidence — only once a passive criterion first signals a suspected island, so as to minimize the frequency and magnitude of the injected disturbance while retaining a small non-detection zone.

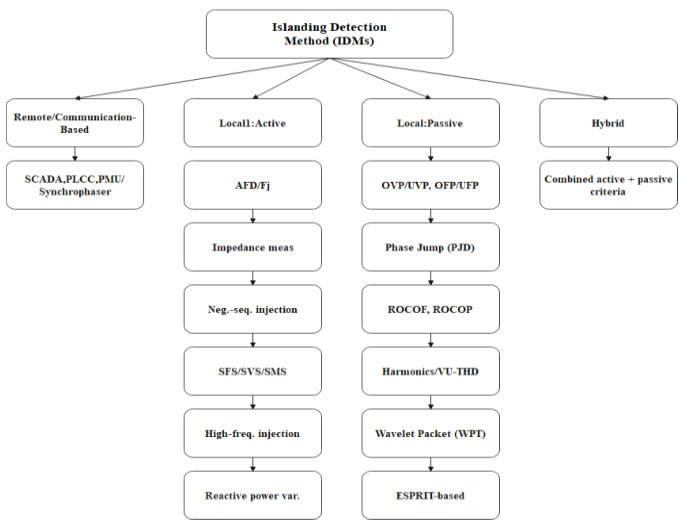


Fig. 1. Taxonomy of islanding detection methods (IDMs).

## 4. REMOTE / COMMUNICATION-BASED METHODS

Remote methods detect islanding by monitoring the state of grid-side switching devices directly, rather than inferring it from local electrical measurements. Utility-level methods insert a low-value impedance at the substation to create a detectable mismatch when the feeder is de-energized; this achieves, in principle, a near-zero non-detection zone, but the additional hardware is costly and the response can be slow.

Communication-based methods instead rely on real-time signalling between the DG, the protection system and a monitoring centre: when the intervening breaker opens, an alarm is raised and the DG is tripped or reconfigured accordingly. Reported implementations include Supervisory Control and Data Acquisition (SCADA) systems, Power Line Carrier Communication (PLCC), synchrophasor or Phasor Measurement Unit (PMU) based schemes, auto-ground switches, and Signal Produced by Disconnect (SPD) methods.

Communication-based methods are attractive because they present a negligible or zero NDZ and, unlike active local methods, impose no continuous power-quality penalty. They are correspondingly favoured in multi-inverter systems, where the effectiveness of many local methods degrades as the number of parallel-connected units increases. Their principal drawback is economic: the communication and monitoring infrastructure represents a capital cost that is difficult to justify for small DG installations, which is why local (active, passive and hybrid) methods continue to dominate in the research literature reviewed below.

## 5. LOCAL METHODS

### *A. Active Islanding Detection Methods*

Active methods intentionally superimpose a small, periodic disturbance on the DG's output current or voltage reference. While the main grid remains connected, its low source impedance suppresses the effect of this disturbance almost entirely; once the grid is disconnected, the same disturbance drives a measurable deviation in a monitored parameter — frequency, voltage, power or impedance — at the point of common coupling (PCC), which is used as the detection signal.

***1) Active Frequency Drift (AFD) and Frequency Jump (FJ):*** Conventional AFD distorts the inverter output current near each zero-crossing to bias the PCC frequency away from nominal when islanded; its detection speed and NDZ are limited by the total harmonic distortion (THD) it is permitted to inject [2],[7],[8],[19]. A modified current-distortion waveform has been shown to reduce injected THD by roughly 30% relative to classical AFD while improving detection speed and shrinking the NDZ [19]. The Frequency Jump (FJ) method modifies AFD by inserting a dead zone into the current waveform only once every few cycles rather than every cycle; because the PCC voltage waveform is not distorted while grid-connected, a jump in the measured frequency after disconnection is an effective islanding indicator for single-inverter systems, although — like AFD — its effectiveness decreases as the number of parallel inverters increases [23].

***2) Impedance Measurement (IM):*** This family of methods estimates the grid-side impedance from the response to an injected harmonic current, using the sharp rise in apparent impedance after grid loss as the detection criterion. Under unbalanced grid impedance the induced harmonic voltage becomes asymmetric, degrading detection accuracy; a dual-frequency harmonic-injection scheme has been proposed that restores accurate impedance estimation for both balanced and unbalanced three-phase feeders without requiring additional measurement hardware, at the cost of a modestly tighter measurement-precision requirement [18].

***3) Negative-Sequence Current Injection:*** A disturbance injected through the q-axis current controller of a converter interfaced to multiple permanent-magnet synchronous-generator (PMSG) based DG units forces a pronounced post-islanding frequency deviation that a second-order band-pass filter combined with an absolute-frequency-variation criterion can detect within 178 ms, even under the most adverse islanding condition for PMSG-based DG [4],[20]. A related approach applies a Decoupled Double Synchronous Reference Frame (DDSRF) phase-locked loop (PLL) to independently control the positive- and negative-sequence current, and detects islanding from the variation in negative-sequence voltage that results from injecting 2–3% negative-sequence current from a battery energy storage system (BESS) [33].

***4) Phase-PLL Perturbation:*** This method introduces a disturbance at the inverter output and infers islanding from the resulting PCC voltage behaviour, which depends on the impedance connected at the PCC; detection is implemented using the Goertzel algorithm to track the induced phase deviation efficiently [17].

***5) Virtual Capacitor / Virtual Inductor Schemes:*** An enhanced hierarchical control structure for islanded microgrids built from parallel LCL-filtered voltage-source inverters has been reported, incorporating a primary control loop with an additional phase-shift term, a secondary control loop for voltage-amplitude and frequency restoration, and multiple inner current-loop damping schemes — virtual positive-, virtual negative- and variable-harmonic-sequence impedance loops — for reactive- and harmonic-power sharing, together with active damping via LCL capacitor-current feedback; small-signal eigenvalue analysis confirmed an over-damped, stable response [3].

***6) High-Frequency Signal Injection:*** A master–slave scheme has been proposed for microgrids with multiple parallel inverters, in which a single master inverter injects a high-frequency signal used by the remaining (slave) units for islanding detection. Slave inverters operate in a high-frequency current-cancellation mode to avoid interference, and if the master fails or grid conditions change significantly, the remaining inverters dynamically and autonomously re-elect a new master using deterministic performance criteria, without requiring inter-inverter communication [16].

***7) Reactive-Power Variation:*** This family superimposes a small reactive-power perturbation on the inverter output and detects islanding from the resulting mismatch in reactive power, voltage magnitude or active/reactive power observed during the disturbance [3],[11],[21]. A perturb-and-observe (P&O) reactive-power scheme has been shown to supply high-quality power to critical loads throughout the clearing interval without altering the output current, to remain immune to load changes occurring during compensation, and to improve reactive-power sharing without compromising voltage regulation or introducing large power transients [13].

***8) Sandia Frequency Shift (SFS) / Active Frequency Drift with Positive Feedback (AFDPF):*** SFS applies positive feedback between the measured PCC frequency deviation and the injected current's frequency bias, accelerating frequency drift once islanded. Analytical studies confirm that the frequency-dependence of the local load's active power has no material effect on SFS's NDZ or detection capability, and that other frequency-drift methods (classical AFD, slip-mode frequency shift) are similarly insensitive to this factor [15],[28].

***9) Sandia Voltage Shift (SVS):*** Analogous to SFS but applied to voltage amplitude rather than frequency: positive feedback between the measured PCC voltage deviation and the inverter's current/power output accelerates voltage drift once the stabilizing effect of the grid is removed, while grid-connected operation leaves the voltage amplitude essentially undisturbed.

***10) Sliding-Mode Frequency Shift (SMS) / Active Phase Shift (APS):*** This method applies positive feedback to the phase angle of the feed-forward voltage in the inverter's current-control loop, so that the phase shift tracks the grid-frequency deviation. Once islanded, the resulting lead/lag between inverter output voltage and PCC voltage generates a reactive-current component that drives the frequency out of the permissible band, producing a detectable drift [8],[31].

## *B. Passive Islanding Detection Methods*

Passive methods monitor one or more system variables continuously and declare an island when a threshold is crossed, without injecting any disturbance into the system. They therefore impose no power-quality penalty, but are inherently subject to a non-detection zone whenever the power mismatch between the DG and its local load at the instant of islanding is small.

***1) Over/Under-Voltage and Over/Under-Frequency Protection (OVP/UVP, OFP/UFP):*** The oldest and still most widely deployed passive scheme trips the DG when the PCC voltage or frequency leaves a fixed band. The size of the resulting NDZ depends strongly on the load — specifically on how unevenly the active-power mismatch ($\Delta P/P$) is distributed — and the method's reliability degrades further when multiple DG units collectively supply a large share of the local active power, since the aggregate mismatch at the instant of islanding can then fall inside the NDZ [32].

***2) Phase Jump Detection (PJD):*** Synchronous-reference-frame PLLs, standard in three-phase DG controllers, track the grid phase angle while connected; once islanded, the PLL output jumps toward the resonant frequency of the local load rather than the nominal grid frequency, and this jump is used as the detection signal [35].

***3) Voltage and Current Harmonic Monitoring:*** For grid-connected PV systems operated under constant-current control, the inverter's self-generated harmonic content can be monitored directly as an islanding indicator, combining power-quality benefits with a reduced NDZ relative to purely threshold-based passive schemes [18],[34].

***4) Rate of Change of Output Power (ROCOP):*** Because the loss of the grid connection generally produces an abrupt load-power change, dP/dt measured over a few cycles rises much faster once islanded than it would for an equivalent load change while grid-connected; the DG is tripped once the integrated power change exceeds a threshold [26].

***5) Rate of Change of Frequency (ROCOF):*** ROCOF relays trip on the measured df/dt and have long been used for both under-frequency load shedding (UFLS) and islanding detection. A centralized ROCOF-based UFLS scheme applied to a small isolated power system has been shown to track the optimal amount of load to shed almost as closely as a hypothetical ideal scheme [12]. For inverter-interfaced DG specifically, new ROCOF threshold settings, together with a low-frequency current-injection scheme through the grid-side voltage-source converter of a doubly-fed induction generator, extend conventional ROCOF relaying to distinguish genuine islanding events from other frequency disturbances — an "active ROCOF relay" [10].

***6) Rate of Change of Frequency over Power (ROCFOP) and Reactive-Power–Frequency Droop:*** This approach combines a reactive-power-versus-frequency droop with ROCOF, designing the injected reactive power to remain small during normal grid-connected operation [6],[9]. Inverter-based DG units at different locations have been shown to exhibit correlated frequency-variation (FV) signatures under a linear reactive-power disturbance (RPD); synchronizing the RPD slope across units — without requiring inter-unit communication — both limits the disturbance while grid-connected and increases the reactive-power mismatch (and hence detection sensitivity) once islanded, with reported robustness to inverter power factor, the number of parallel units, and the connection configuration [8].

***7) Voltage Unbalance / Total Harmonic Distortion (VU/THD):*** This scheme monitors voltage unbalance and THD as the primary (passive) criterion, and is often combined with an active bilateral reactive-power-variation (BRPV) trigger that arms only when VU/THD first indicates a suspected island — improving detection performance without a continuous power-quality cost [7].

***8) ESPRIT-Based Detection:*** Estimation of Signal Parameters via Rotational Invariance Techniques (ESPRIT), a statistical signal-processing algorithm, has been applied to extract modal amplitude, oscillation-frequency, damping-factor and phase features from a damped-sinusoid model of the PCC voltage and frequency waveforms; a naïve-Bayes classifier trained on cases generated from the IEEE 34-bus test feeder was used to discriminate islanding from non-islanding events, with performance verified by cross-validation [1].

***9) Rate of Change of Phase-Angle Difference (ROCPAD):*** Voltage and current phasors estimated at the DG terminal using an asynchronous transformation-based algorithm can be used to compute the phase-angle difference and its rate of change; this criterion has been shown to remain effective in cases where conventional ROCOF relaying fails [36].

***10) Change of Source Impedance ("Harmonic Amplitude Jump"):*** Conceptually related to active impedance measurement, this passive variant exploits the fact that an intentionally injected harmonic is normally overwhelmed by the low-impedance utility source; once the utility disconnects, the same harmonic becomes clearly observable at the PCC.

***11) Wavelet Packet Transform (WPT):*** WPT has been applied to the PCC voltage of a grid-connected PV inverter, computing a normalized logarithmic energy entropy (NLEE) from the decomposed signal and feeding it to a back-propagation neural network (BPNN) that classifies islanding without requiring a fixed threshold; reported detection time was within 40 ms, including under the difficult near-zero power-mismatch condition [14].

***12) Voltage-Ripple-Based Detection:*** Across a wide range of MATLAB/Simulink-simulated operating conditions, monitoring the ripple content of the ROCOF or PCC voltage waveform (with an appropriate delay-time allowance) has been shown to detect islanding even at zero power mismatch, faster than conventional ROCOF-ripple and other passive schemes, and well within the trip-time limits of IEEE 1547 and UL 1741 [37].

***13) Transient-Component-Based Detection:*** Rather than relying on the steady-state or slowly-varying value of frequency, voltage or power, this approach extracts features from the brief transient that follows a switching event, offering a feature domain that is complementary to, and can be combined with, the steady-state criteria described above [22].

## 6. HYBRID ISLANDING DETECTION METHODS

Hybrid schemes combine an active and a passive criterion, typically arming the active perturbation, or accepting it as confirmatory evidence, only once a passive criterion first flags a suspected island. This design retains much of the low NDZ characteristic of active methods while confining their power-quality penalty to the brief interval following a genuine (or suspected) loss of grid connection. Table I lists representative hybrid techniques proposed between 2006 and 2021, illustrating the steady research interest in this category and the range of active/passive combinations explored — from early combinations of sliding-mode frequency shift with phase-jump detection under varying quality factor, through reactive-power-droop and positive-feedback combinations, to more recent machine-learning-assisted (e.g., genetic-algorithm / multilayer-perceptron) and voltage-unbalance/THD-triggered BRPV schemes.

**TABLE I**

**REPRESENTATIVE HYBRID ISLANDING DETECTION TECHNIQUES (2006–2021)**

| Technique | Year Proposed |
|---|---|
| SMS & PJD with Varying QF | 2006 |
| VU & Frequency Set-Point | 2007 |
| ROCOV and Real Power Curve | 2009 |
| SFS & Q-F Drop Curve | 2010 |
| Positive Feedback and RPV | 2013 |
| SFS & Q-F Combination | 2014 |
| Q-F Droop & RPV | 2014 |
| Positive Feedback & VU | 2014 |
| NJSMS & Q-F | 2015 |
| SFS & ROCOF | 2015 |
| Reactive Power Injection & ROCOF | 2016 |
| VI and PLL | 2017 |
| FD & SFS | 2017 |
| TIV & PSSCA | 2018 |
| VV, VU & ROCOF | 2018 |
| GA & MLP | 2019 |
| VU/THD & BRPV | 2020 |
| ROCOV & ROCOP | 2020 |
| ROCOV & ROCOAP | 2021 |

## 7. COMPARATIVE DISCUSSION

Table II summarizes the qualitative trade-offs among the four method families reviewed above. Remote methods offer the smallest NDZ and the least power-quality impact but the highest infrastructure cost, which limits their use to larger DG installations or aggregated feeders. Active methods achieve a small, well-characterized NDZ and generally degrade gracefully as inverter count increases only when a coordinated (master–slave or synchronized-disturbance) architecture is used; their principal cost is a continuous, if small, degradation of power quality. Passive methods impose no power-quality penalty and no additional cost, but their NDZ — and hence their reliability — depends directly on the DG/load power mismatch at the instant of islanding, which cannot be controlled or predicted in advance; several of the passive schemes reviewed above (WPT, voltage-ripple, ROCPAD) were specifically developed to shrink this NDZ using richer signal features rather than simple thresholds. Hybrid methods aim to combine the low NDZ of active methods with the low power-quality impact of passive methods by restricting the active perturbation to intervals where a passive criterion has already raised suspicion, at the cost of increased detection-logic complexity and, in most reported schemes, a modest increase in overall detection latency relative to a purely active scheme operating continuously.

A recurring theme across the reviewed literature is that a technique's performance is rarely independent of the DG technology or the network topology for which it was validated: several active and passive schemes reviewed above were developed and demonstrated for a specific DG type (chiefly inverter-interfaced PV) or for a specific inverter-count regime, and their NDZ, detection time or false-trip behaviour can change materially outside that regime. This observation — together with the residual power-quality/NDZ trade-off inherent to purely active or purely passive schemes — motivates the hybrid framework proposed in Section X.

**TABLE II**

**QUALITATIVE COMPARISON OF ISLANDING DETECTION METHOD FAMILIES**

| Method Family | Non-Detection Zone (NDZ) | Power-Quality Impact | Multiple-Inverter Behaviour | Relative Infrastructure Cost | Typical Detection Speed |
|---|---|---|---|---|---|
| Remote / Communication-based | Negligible to zero | None | Good, largely independent of inverter count | High | Fast (breaker-status dependent) |
| Active (local) | Small, well-characterized | Continuous, low-level (THD / reactive-power injection) | Degrades with inverter count unless coordinated (master–slave, synchronized disturbance) | Low to moderate | Fast to moderate |
| Passive (local) | Load/mismatch-dependent; largest near zero power mismatch | None | Generally good; unaffected by inverter count | Low | Fast at large mismatch; slow or unreliable near zero mismatch |
| Hybrid (active + passive) | Small, approaching active-method performance | Intermittent, confined to suspected-island interval | Good with coordination | Moderate | Moderate (passive trigger followed by active confirmation) |

# 8. RELIABILITY CONSIDERATIONS FOR ISLANDING-CAPABLE MICROGRIDS

Beyond detection accuracy and speed, an islanding-capable microgrid's overall reliability depends on the probability that the DG, its converter and its protection logic are actually available and functioning correctly at the moment islanding occurs. A short-term reliability-assessment method for islanded microgrids based on a time-varying-probability ordered-tree screening algorithm has been proposed, which reduces the state space by retaining only high-probability system states at each time step, defines two categories of load-point supply interruption according to their impact range, and computes the loss-of-load probability (LOLP) and expected-demand-not-supplied (EDNS) indices; the approach was validated on a European low-voltage microgrid model in MATLAB [38].

Because many microgrids increasingly host DC-type renewable resources, a Bayesian-network (BN) based probabilistic framework for the reliability analysis of renewables-dominated DC microgrids has been developed, incorporating indices for loss of renewable power supply, voltage rise and power-flow reversal, supported by a fast linearized power-flow algorithm and validated against Monte-Carlo simulation; the results indicate that high renewable penetration affects different reliability indices unevenly [39].

At the converter level, it has been observed that microgrid reliability studies commonly assume an oversimplified constant failure rate for power converters, ignoring their internal semiconductor arrangement and loading; a hierarchical reliability model has instead been proposed that begins with converter-level reliability (accounting for semiconductor arrangement and loading condition) and builds up to a full microgrid reliability-block diagram, also examining the effect of redundant converter designs [40]. Related work has extended reliability evaluation to active distribution networks that explicitly include islanding dynamics, and general reliability-modeling frameworks for smart power systems provide the underlying methodological basis for these microgrid-specific studies [41],[42]. Collectively, these studies indicate that islanding detection cannot be evaluated in isolation from the reliability of the DG, converter and protection hardware that must act on the detection signal — a consideration incorporated into the validation plan described in Section XI.

## 9. RESEARCH GAP AND PROBLEM STATEMENT

The review above indicates three recurring limitations. First, purely passive methods — the most widely deployed in practice owing to their negligible cost and zero power-quality impact — remain unreliable precisely when the DG/load power mismatch at islanding is small, which is also the condition most likely to occur in a well-compensated distribution feeder. Second, purely active methods reduce this non-detection zone but do so by continuously injecting a disturbance into the network, degrading power quality even during normal grid-connected operation, and several active schemes lose effectiveness as the number of parallel-connected inverters grows unless an explicit coordination mechanism is added. Third, most reported methods — active, passive or hybrid — are validated for, and implicitly tuned to, a single DG technology, so that a distribution feeder hosting a heterogeneous mix of DG types cannot be assumed to inherit the reported NDZ or detection-time performance of any individual method without re-validation. Some recent work has begun to target this heterogeneity gap directly — detection schemes explicitly designed for hybrid DG mixes have reported a reduced non-detection zone relative to methods tuned to a single DG technology [24] — reinforcing the case for continued research in this direction.

These limitations motivate the central problem addressed by this work: to design and validate an islanding detection technique that (i) retains the essentially zero power-quality cost of a passive scheme during normal operation, (ii) actively shrinks the non-detection zone near the near-zero-mismatch condition where passive schemes are weakest, and (iii) is evaluated for robustness across more than one DG type and under multiple-inverter operation, using dynamic parameters — specifically the coupling between reactive power and frequency, and between active power and voltage — at the PCC [5].

## 10. PROPOSED FREQUENCY–REACTIVE POWER HYBRID ISLANDING DETECTION FRAMEWORK

### *A. Design Rationale*

Guided by the gaps identified in Section IX, this work proposes a hybrid islanding detection framework that combines a passive frequency/voltage monitoring stage with a small, closed-loop reactive-power perturbation. The perturbation is designed to remain within the power-quality limits of IEEE 1547 during normal, grid-connected operation, and is amplified through positive feedback once the passive stage first flags a suspected deviation. Because the perturbation acts on reactive rather than active power, it is expected to be applied with a smaller impact on delivered real power and, unlike several of the active methods reviewed in Section V-A, does not require continuously distorting the inverter's active-current waveform.

## B. System Architecture

Fig. 2 shows the proposed control architecture. The DG feeds its output through an inverter and an output filter to the point of common coupling (PCC), where it is measured by a dedicated measurement unit before connecting to the three-phase local load and, through the PCC, to the utility grid. The measurement unit provides voltage and current waveforms to a frequency-measurement block, whose output is compared against a frequency reference (freq_ref) in a comparator stage. The comparator output, together with a reactive-current reference (Iq_ref), is supplied to a control unit that adjusts the inverter's reactive-current injection and closes the loop back to the inverter. Under normal grid-connected operation, the grid's low source impedance holds the PCC frequency close to freq_ref despite the injected reactive-power perturbation, so the comparator output remains small. Once the grid disconnects, the load/generation reactive-power mismatch causes the PCC frequency to drift measurably in response to the same perturbation; the comparator output grows accordingly, and the control unit uses this signal — together with the coordinated passive frequency/voltage check — to declare islanding and initiate DG disconnection.

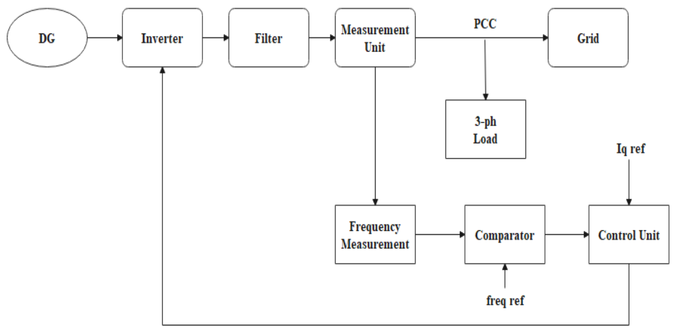


Fig. 2. Proposed frequency–reactive power hybrid islanding detection architecture.

## C. Working Principle

The proposed detection algorithm proceeds as follows.

1) Continuously measure voltage and current at the PCC and compute the instantaneous frequency and RMS voltage.

2) Apply a small reactive-current perturbation (Iq_ref) at the inverter output, sized to remain within the harmonic / power-quality limits of IEEE 1547 during normal, grid-connected operation.

3) Compare the measured frequency against freq_ref; while the deviation remains below a first (passive) threshold, continue normal operation.

4) If the deviation crosses the first threshold, treat this as a suspected-island flag and increase the gain of the reactive-power-to-frequency feedback loop (positive feedback), accelerating any further frequency drift consistent with islanding.

5) If the accelerated frequency deviation crosses a second, confirmatory threshold within a bounded time window, declare islanding and command the control unit to trip the DG's point-of-interconnection breaker.

6) If the deviation returns below the first threshold without crossing the second — for example, due to a transient unrelated to islanding — reset the feedback gain to its normal value to avoid a nuisance trip.

This two-stage (passive-flag, active-confirm) structure is intended to keep the reactive-power perturbation, and its associated power-quality cost, small during normal operation while still shrinking the non-detection zone relative to a purely passive frequency/voltage scheme, consistent with the hybrid-method rationale reviewed in Section VI.

## D. Expected Advantages

Because the perturbation is reactive rather than active power, and because its magnitude is increased only once a suspected island has already been flagged passively, the proposed framework is expected to (i) impose a smaller continuous power-quality cost than continuously operating active methods such as classical AFD or SMS; (ii) achieve a smaller non-detection zone than a purely passive frequency/voltage scheme, particularly near the zero-active-power-mismatch condition; and (iii) remain applicable across DG technologies, since the perturbation is applied at the inverter's reactive-current reference rather than relying on a technology-specific active-power or harmonic signature. These expected advantages, framed relative to the qualitative comparison in Table II, form the basis of the validation methodology described next.

## 11. VALIDATION METHODOLOGY

The proposed framework will be implemented and evaluated in MATLAB/Simulink, following the three-stage plan outlined below.

***1) Baseline Reproduction:*** The passive frequency/voltage stage and a representative set of the active and hybrid methods reviewed in Sections V and VI will first be reproduced in simulation, using standard test feeders and DG models, to establish a common baseline non-detection zone and detection-time benchmark against which the proposed method can be compared.

***2) Feature Extraction and Perturbation Design:*** Voltage and current waveforms will be recorded at the PCC of a target DG under a matrix of operating conditions spanning quality factor, active/reactive power mismatch, and — for the multiple-inverter case — inverter count and disturbance-synchronization strategy. The reactive-current perturbation magnitude and the two-stage threshold/gain parameters described in Section X-C will be tuned against this data set.

***3) Standards-Referenced Verification:*** The resulting non-detection zone, detection time and grid-connected total harmonic distortion will be verified against the trip-time and power-quality limits specified in IEEE 1547 and UL 1741, and compared against the baseline methods reproduced in Stage 1 using the qualitative criteria of Table II — NDZ, power-quality impact, multiple-inverter behaviour and detection time — rendered quantitatively.

This validation work is scheduled to follow the literature review already completed (Sections II–VIII of this paper) over the course of the doctoral research program, with model preparation, simulation analysis and results dissemination planned across the subsequent research phases.

## 12. CONCLUSION AND FUTURE WORK

This paper reviewed remote, active, passive and hybrid islanding detection methods reported in the recent IEEE literature, and organized their characteristic trade-offs — non-detection zone, power-quality impact, cost, and behaviour under multiple parallel-connected inverters — with reference to the IEEE 1547 and UL 1741 anti-islanding requirements. The review indicates that no single existing method is simultaneously free of a non-detection zone, free of a power-quality penalty, low-cost, and robust across heterogeneous DG technologies and inverter counts, motivating continued research into hybrid schemes that combine the complementary strengths of active and passive detection.

Building on this analysis, a hybrid islanding detection framework was proposed that couples a passive frequency/voltage monitoring stage with a closed-loop reactive-power perturbation whose gain is increased through positive feedback once a suspected island is passively flagged. The framework's architecture and detection algorithm were described, together with a three-stage MATLAB/Simulink validation methodology referenced against IEEE 1547 and UL 1741. Future work will implement this methodology and report the resulting non-detection zone and detection-time performance relative to the baseline methods reviewed in this paper; it will also extend the evaluation to microgrids with multiple, heterogeneous DG units, and may draw on fully distributed control architectures reported for islanded AC microgrids to regulate voltage and frequency during the confirmed-island interval without dependence on a central controller [29], consistent with the universal-applicability objective identified in Section IX.

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