A Novel Passive Islanding Detection Method Based on Phase-Locked Loop

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Abstract

The ever-increasing penetration of distributed energy resources in power distribution systems has led to challenges in the detection of islanding. Among different islanding detection methods (IDMs), passive methods are the least intrusive and typically require the lowest investment cost. However, they generally suffer from larger non-detection zones (NDZs) and higher nuisance detection ratios as compared to active, hybrid, and remote IDMs. This study provides an overview of the criteria outlined in the existing technical literature for the performance evaluation of IDMs, a review and comparison of the existing passive IDMs, and an analysis of the phase-locked loop (PLL) behaviour under grid-connected and islanded conditions using its quasi-static model. Based on the results of these studies, a novel passive IDM is developed that utilizes the PLL error to detect islanding with a small NDZ and high speed.

The performance of the proposed IDM is evaluated under various islanding and non-islanding disturbances. The performance evaluation studies are conducted through simulations in the PSCAD software environment as well as experimental tests using a hybrid microgrid test platform. The study results indicate that the proposed method: (i) can detect islanding in less than two cycles, which is well below the requirements of the IEEE 1547 standard, (ii) leads to a small NDZ and can identify islanding with only ±5% power mismatch, (iii) does not cause false detection of non-islanding disturbances as islanding, and (iv) is robust against noise.

Keywords: Islanding detection, distributed energy resources, non-detection zone, phase-locked loop
Summary for Lay Audience

Under normal conditions, the utility grid and distributed energy resources (DERs) operate in parallel to supply power to consumers. If for any reason (e.g., a fault) an upstream circuit breaker opens and disconnects a DER from the rest of the grid, an island may form where the DER continues to feed the adjacent loads without the voltage and frequency support from the grid. Unintentional islanding must be rapidly detected since it leads to safety hazards for utility workers and maintenance personnel.

There are several categories of islanding detection techniques such as passive and active methods. A desirable islanding detection scheme is dependable, secure, robust, fast, cost-effective and non-intrusive. None of the existing islanding detection approaches meets all these requirements. For instance, active methods are generally reliable but degrade power quality. In contrast, passive methods do not adversely affect the power quality but may fail to detect islanding in some cases. This thesis introduces a novel passive islanding detection method which is fast and inexpensive. It operates reliably under most islanding/non-islanding scenarios and does not require communication systems. The proposed method is evaluated and validated through both simulation studies and experimental tests.
To Behnam.

For his advice, his patience, and his faith.

And because he always understood.
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<tr>
<td>DER</td>
<td>Distributed Energy Resource</td>
</tr>
<tr>
<td>PV</td>
<td>Photovoltaic</td>
</tr>
<tr>
<td>WT</td>
<td>Wind Turbine</td>
</tr>
<tr>
<td>BESS</td>
<td>Battery Energy Storage System</td>
</tr>
<tr>
<td>PCC</td>
<td>Point of Common Coupling</td>
</tr>
<tr>
<td>IDM</td>
<td>Islanding Detection Method</td>
</tr>
<tr>
<td>NDZ</td>
<td>Non-Detection Zone</td>
</tr>
<tr>
<td>UOV</td>
<td>Under/Over Voltage</td>
</tr>
<tr>
<td>UOF</td>
<td>Under/Over Frequency</td>
</tr>
<tr>
<td>ROCOV</td>
<td>Rate of Change of Voltage</td>
</tr>
<tr>
<td>ROCOF</td>
<td>Rate of Change of Frequency</td>
</tr>
<tr>
<td>ROCOP</td>
<td>Rate of Change of Power</td>
</tr>
<tr>
<td>PLL</td>
<td>Phase-Locked Loop</td>
</tr>
<tr>
<td>PMSG</td>
<td>Permanent Magnet Synchronous generator</td>
</tr>
<tr>
<td>HHT</td>
<td>Hilbert Huang Transform</td>
</tr>
<tr>
<td>ACF</td>
<td>Auto-Correlation Function</td>
</tr>
<tr>
<td>ANN</td>
<td>Artificial Neural Network</td>
</tr>
<tr>
<td>PNN</td>
<td>Probabilistic Neural Network</td>
</tr>
<tr>
<td>SRF</td>
<td>Synchronous Reference Frame</td>
</tr>
<tr>
<td>IDS</td>
<td>Islanding Detection Signal</td>
</tr>
<tr>
<td>FD</td>
<td>False Detection</td>
</tr>
</tbody>
</table>
Nomenclature

\( Q_f \) \hspace{1cm} \text{Load quality factor} \\
\( R \) \hspace{1cm} \text{Equivalent lumped load resistance} \\
\( L \) \hspace{1cm} \text{Equivalent lumped load inductance} \\
\( C \) \hspace{1cm} \text{Equivalent lumped load capacitance} \\
\( V_n \) \hspace{1cm} \text{System nominal voltage} \\
\( f_n \) \hspace{1cm} \text{System nominal frequency} \\
\( P_{Load} \) \hspace{1cm} \text{Load active power} \\
\( V_q \) \hspace{1cm} \text{q-axis component of PCC voltage} \\
\( \Delta P \) \hspace{1cm} \text{Generation-load active power mismatch} \\
\( \Delta Q \) \hspace{1cm} \text{Generation-load reactive power mismatch} \\
\( C_{norm} \) \hspace{1cm} \text{Normalized capacitance} \\
\( f_0 \) \hspace{1cm} \text{Load resonant frequency} \\
\( V_d \) \hspace{1cm} \text{d-axis component of PCC voltage} \\
\( v_a, v_b, \text{ and } v_c \) \hspace{1cm} \text{Instantaneous voltages of phase a, b, and c} \\
\( \omega' \) \hspace{1cm} \text{Angular frequency tracked by PLL} \\
\( V_{grid} \) \hspace{1cm} \text{Grid voltage amplitude} \\
\( I_{inv} \) \hspace{1cm} \text{Inverter current amplitude reference} \\
\( \varphi_{inv} \) \hspace{1cm} \text{phase shift angle due to the presence of the reactive components in the load and grid impedances} \\
\( z_L \) \hspace{1cm} \text{Local load impedance} \\
\( z_g \) \hspace{1cm} \text{Grid impedance} \\
\( \omega \) \hspace{1cm} \text{Grid angular frequency} \\
\( K_1 \) \hspace{1cm} \text{Grid synchronization loop gain} \\
\( K_2 \) \hspace{1cm} \text{Self synchronization loop gain}
<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \theta )</td>
<td>PCC phase angle</td>
</tr>
<tr>
<td>( \theta' )</td>
<td>Phase angle tracked by PLL</td>
</tr>
<tr>
<td>( v^- )</td>
<td>Grid synchronization loop voltage</td>
</tr>
<tr>
<td>( v^+ )</td>
<td>Self synchronization loop voltage</td>
</tr>
<tr>
<td>( R_f )</td>
<td>Fault resistance</td>
</tr>
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</table>
Chapter 1

1 Introduction

1.1 Background

Distributed energy resources (DERs) are dispersed power generation units, e.g., photovoltaic (PV) systems and wind turbines (WTs), or energy storage units like battery energy storage systems (BESSs), that are integrated into the distribution systems [1], [2].

The utility grid and DERs work in parallel to supply the local load. Islanding is defined as a condition in which a portion of the utility system is energized by DERs while it is electrically separated from the rest of the utility grid [3]–[5]. This phenomenon can be intentional or unintentional [6], [7]. Intentional islanding is a controlled event that is typically triggered for scheduled operations such as system maintenance, while unintentional islanding happens due to unforeseen events such as faults and other disturbances in the power system [8].

Unintentional islanding must be detected with high speed and reliability to minimize safety hazards and prevent equipment damage [4], [9]. The
challenges posed by unintentional islanding include but are not limited to [10], [11]:

- Health hazards for utility workers who may not be aware that the line is energized by DER(s).

- Unsynchronized reconnection of the island to the grid may result in excessively large currents and damage to the DERs. Also, it may cause protective relays to trip.

Islanding detection methods (IDMs) can be broadly categorized into local and remote techniques [12]–[15], as shown in Figure 1.1. Remote IDMs [16]–[20] rely on communication between the utility grid and the DERs to provide zero non-detection zone (NDZ), meaning they are capable of islanding detection even with perfect generation-load power balance. However, remote IDMs are costly due to the required communication systems [12], [14], [21] and suffer from the risk of communication failure. Local IDMs, which do not utilize remote communication, are further divided into passive, active, and hybrid methods [12]–[14].
Passive methods [22]–[27] monitor system parameters such as voltage and frequency and compare them with pre-determined thresholds to detect islanding [28]. An advantage of passive IDMs is that they do not degrade power quality. The conventional passive methods are simple, cost-effective, easy to implement, and independent of DER control strategies. However, the existing conventional passive IDMs generally suffer from a large NDZ, i.e., may fail to detect islanding when there is a small generation-load power mismatch [27], [29], [30].

Signal processing-based [31]–[33] and artificial intelligence-based techniques [34]–[36] are other categories of IDMs that are considered as improved
passive methods [4], [37], [38]. Although the improved passive IDMs have alleviated some of the shortcomings of the conventional passive techniques, they generally suffer from increased cost and complexity, high computational burden, and in some cases noise sensitivity [21], [39].

An active IDM [40]–[44] forces a specific system parameter to deviate and exceed the corresponding thresholds by injecting a perturbation signal [4], [30]. Active IDMs benefit from small NDZs but may adversely affect power quality and system stability [45], [46], suffer from low speed [29], [47], and become less effective in systems with multiple DERs [21], [48].

In a hybrid IDM [13], [49]–[51], active islanding detection is enabled only when islanding is suspected by the passive scheme [26], [52]. Hybrid IDMs benefit from less power quality degradation as compared to active IDMs but do not eliminate the power quality and stability issues of active methods [46].

Among the existing passive IDMs, those operating based on under/over voltage (UOV) [5], [53], under/over frequency (OUF) [5], [9], [53], [54], rate of change of voltage (ROCOV) [14], [55], rate of change of frequency (ROCOF) [56]–[58], and rate of change of power (ROCOP) [14], [59] are the most widely used [9], [60]. These methods are prone to false detection due to faults and load fluctuations [61], [62] and are not able to detect islanding when
the generation and load are closely matched [25], [30], [62], [63]. However, if the shortcoming of large NDZ is overcome, passive methods can be suitable candidates for practical applications owing to their simplicity and cost-effectiveness [27], [64]. A more detailed review of the existing passive IDMs is presented in Chapter 2.

Several studies [65]–[68] have proposed to utilize the deviation of phase-locked loop (PLL) output (i.e., frequency) during islanding to detect islanding. However, frequency-based islanding detection is not always reliable. In addition, most of the studies have not used any models for the prediction of PLL behaviour under islanded conditions and thus, they lack design procedures and generalizability.
1.2 Statement of the Problem

As discussed in part 1.1, active IDM\textsuperscript{s} degrade power quality and may suffer from low speed. Also, they are not reliable methods for islanding detection of multi-DER systems. On the other hand, the existing passive IDMs either suffer from large NDZ\textsuperscript{s} or are computationally expensive and sensitive to noise. This requires the development of a simple and robust IDM. The high costs associated with remote IDMs limit their practical application. Therefore, there is a need to develop a fast and reliable IDM that is cost-effective, does not degrade power quality, does not require communication, and can be applied to multi-DER systems.

1.3 Research Objectives

The objectives of this research are (i) developing a passive IDM with high speed, high reliability, and a small NDZ, (ii) devising a systematic approach for setting the parameters of the proposed method, and (iii) verifying the acceptable performance of the proposed IDM under various islanding and non-islanding scenarios through simulation studies and experimental tests.
1.4 Methodology

The methodology to achieve the above-mentioned objectives includes:

- Developing an algorithm to detect islanding based on the variations of the PLL error.
- Verifying the acceptable performance of the proposed IDM in grid-connected inverters through time-domain simulation of the Canadian benchmark medium-voltage distribution system [69]–[71] in the PSCAD software environment.
- Investigating the performance of the proposed IDM under practical conditions through experimental tests using a microgrid test platform.
- Evaluating and comparing the performance of the proposed IDM with those of the five most commonly used passive IDMs, which operate based on UOV, UOF, ROCOF, ROCOV, and ROCOP.
1.5 Study Systems

The following subsections describe the utilized study systems and their roles in the evaluation of the proposed IDM.

1.5.1 Study System 1: Canadian Benchmark Rural Distribution Network

A detailed and realistic model of the modified Canadian benchmark rural distribution network [69]–[71], including the switching models of the converters and the associated control systems, is utilized for simulation studies in the PSCAD software environment. The study system 1 includes a 3.5 MW PV generation unit, a 4 MW wind power plant composed of two 2 MW permanent magnet synchronous generator (PMSG)-based WTs, and two 2 MW BESSs\(^1\), as shown in Figure 1.2. The study system 1 is used for the performance evaluation of the proposed IDM, including the detection time and nuisance detection ratio\(^2\). For a fair comparison between the IDMs, the results of the time-domain simulation studies in PSCAD are used to choose the best set of parameters for the investigated passive IDMs.

\(^1\) Refer to Appendix A for the parameters.

\(^2\) Refer to Chapter 2 for the definitions.
Figure 1.2: Study system 1: Canadian benchmark rural distribution network.
1.5.2 Study System 2: IEEE Recommended Test System for Islanding Detection Studies

One of the most widely utilized references for islanding detection requirements of DERs is the IEEE 1547-2018 standard [3]. IEEE 929-2000 [72] also provides recommended practices for the utility interface of PV systems. The test system illustrated in Figure 1.3 is a simplified representation of an islanded system, which is recommended by IEEE 1547 and IEEE 929 for the investigation of NDZ.

![Figure 1.3](image)

Figure 1.3: Study system 2: recommended test system for islanding detection studies according to IEEE 1547-2018 and IEEE 929-2000 recommended practice.

The study system of Figure 1.3 is used for identifying the NDZ of the IDMs under different generation-load power mismatches. The islanding detection requirements outlined in [3] and [72] are summarized in Table 1. The quality factor $Q_f$ in Table 1 describes the aggregate load within the islanded system, which is represented by a parallel RLC branch (as shown in Figure 1.3) to consider the most difficult scenario for islanding detection [8], [73].
Table 1: Islanding Detection Requirements According to IEEE Recommended Practices.

<table>
<thead>
<tr>
<th></th>
<th>IEEE 1547-2018</th>
<th>IEEE 929-2000</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Quality factor</strong></td>
<td>1</td>
<td>2.5</td>
</tr>
<tr>
<td><strong>Detection time</strong></td>
<td>$t &lt; 2$ s</td>
<td>$t &lt; 2$ s</td>
</tr>
<tr>
<td><strong>Normal frequency range</strong></td>
<td>$59.3 , Hz \leq f \leq 60.5 , Hz$</td>
<td>$59.3 , Hz \leq f \leq 60.5 , Hz$</td>
</tr>
<tr>
<td><strong>Normal voltage range</strong></td>
<td>$88% \leq V \leq 110%$</td>
<td>$88% \leq V \leq 110%$</td>
</tr>
</tbody>
</table>

The test system equivalent load parameters $R$, $L$, and $C$ can be calculated as:

$$R = \frac{V_n^2}{P_{Load}}$$  \hspace{1cm} (1)

$$L = \frac{V_n^2}{2\pi f_n Q_f P_{Load}}$$  \hspace{1cm} (2)

$$C = \frac{Q_f P_{Load}}{2\pi f_n V_n^2}$$  \hspace{1cm} (3)

where $P_{Load}$ is the load active power, and $V_n$ and $f_n$ are the system nominal voltage and frequency, respectively.

**1.5.3 Study System 3: Hybrid Microgrid Test Platform**

Study system 3 is a hardware-implemented hybrid microgrid which is used for experimental validation of the proposed passive IDM. This system utilizes a 40 V DC bus and a 16 V three-phase AC bus\(^1\) as shown in Figure 1.4.

---

\(^1\) Refer to Appendix B for the parameters.
Figure 1.4: Study system 3: hybrid microgrid test platform: (a) single-line diagram, and (b) the implemented hardware.
1.6 Contributions

The main contributions of this thesis are listed below.

- The proposed IDM is capable of islanding detection within 2 cycles, which is faster than the requirements of IEEE 1547.

- The parameters of the proposed IDM can be systematically determined for any specific system.

- The NDZ of the proposed method is small as compared to most of the existing passive IDMs while it does not adversely affect power quality and stability and does not require costly computation and communication systems.

- The proposed IDM does not cause false detection of non-islanding events as islanding.

- The proposed method is reliable, i.e., dependable and secure.
Chapter 2

2 Literature Review

In this chapter, first, the criteria for the performance evaluation of IDMs are described. Then, a review of the existing passive IDMs is provided, and finally, a high-level comparison of the existing IDMs is presented.

2.1 Criteria for Performance Evaluation of IDMs

Several criteria are used to determine how reliably and fast an IDM can detect islanding. These criteria include NDZ, detection time, applicability in multi-DER systems, nuisance detection ratio, effect on power quality and stability, and cost.

2.1.1 Non-Detection Zone

The most important indicator in the evaluation of IDMs is the NDZ. It is defined as the operating region of an IDM in which islanding cannot be detected. The aforementioned operating region can be described in either power mismatch space or load parameter space [62], [73], [74].
2.1.1.1 NDZ in the Power Mismatch Space

Under islanded operating conditions, if the DER power output and the load power within the islanded system of Figure 1.3 are closely matched, the variations in voltage and frequency caused by islanding will not be sufficiently large to be detected. The worst-case scenario in the detection of islanding happens when there is no generation-load power mismatch, i.e., \( \Delta P = 0 \) and \( \Delta Q = 0 \) [73], [75].

![NDZ representation in the power mismatch space.](image)

The power mismatch space describes the range of active and reactive power mismatches (\( \Delta P \) versus \( \Delta Q \)) which do not cause the system variables to exceed the corresponding thresholds [48], [62], as depicted in Figure 2.1. The power mismatch space is an effective indicator of NDZ for passive IDM [48], [74].
2.1.1.2 NDZ in the Load Parameter Space

The NDZ of an active frequency drifting method is typically evaluated using the load parameter space [73], [74]. In this method, the DER and load active powers are assumed to be matched, i.e., $\Delta P = 0$. Using (1)-(3), the equivalent load parameters ($R$, $L$, and $C$) are determined. The load parameter space maps the NDZ of an IDM into $C_{norm}$ versus $L$ space [76]. $C_{norm}$ is defined as the ratio of the load capacitance to the capacitance that resonates with the load inductance at the grid frequency and is given by:

$$C_{norm} = \frac{C}{C_{res}} = \frac{C}{C\omega^2L}$$

(4)

One drawback of the $C_{norm}$ versus $L$ space is that different values of $R$ lead to different NDZs in the load parameter space. This issue is addressed in [77] by proposing $Q_f$ versus $f_0$ load parameter space instead, where $f_0$ is the load resonant frequency and $Q_f$ is the load quality factor which can be expressed as:

$$Q_f = R \sqrt{\frac{C}{L}}$$

(5)
2.1.2 Detection Time Delay

Detection time is the time elapsed from the occurrence of islanding to the time instant at which islanding is detected. Fast detection of islanding conditions is necessary to minimize the adverse effects of unintentional islanding [73].

2.1.3 Applicability in Multi-DER Systems

An island in a modern power system may comprise not only more than one DER but also multiple types of DERs. The effectiveness of IDM s may decrease in the multi-DER case, e.g., where multiple inverters rely on power output variation for active islanding detection. As more inverters are added, the unsynchronized alteration of the outputs may lead to an insignificant change in system variables and failure to detect islanding [73], [78].

2.1.4 Nuisance Detection Ratio

IDMs should not detect non-islanding disturbances such as faults and load switching events as islanding. The nuisance detection ratio is defined as the ratio of the number of false detection cases to the total number of islanding detection cases [62]. An excessively sensitive IDM has a small NDZ but is likely to have a high nuisance detection ratio.
2.1.5 **Effect on Power Quality and Stability**

IDMs based on perturbation injection, i.e., active or hybrid, degrade the power quality during islanding and may even trigger instability [38], [62]. Therefore, IDMs with minimum effect on power quality are preferred.

2.1.6 **Cost**

Implementation of some IDMs requires the installation of costly hardware which can limit their practical application. A compromise between cost and performance must be made for real-world applications [73].
2.2 Review of the Existing Passive IDMs

This section provides a review of the existing passive IDMs. In the following parts, the different types of passive IDMs are discussed.

2.2.1 Conventional Passive IDMs

The existing conventional passive IDMs can be categorized into different groups based on the system variables utilized to detect islanding, including UOV, UOF, ROCOV, ROCOF, ROCOP, harmonic detection, voltage unbalance, phase jump detection, and vector shift. The most widely used conventional passive IDMs are discussed below.

2.2.1.1 Under/Over Voltage and Under/Over Frequency

The OUV and OUF protective elements are typically used in grid-connected PV inverters [30], [79]. These elements monitor voltage and frequency at the point of common coupling (PCC) and compare them with pre-determined thresholds. In an islanded system, the voltage and frequency deviations are indicators of the active and reactive power mismatches, i.e., $\Delta P$ and $\Delta Q$ in Figure 1.3 [39], [80], and thus enable islanding detection. Islanding detection based on OUV is simple and cost-effective but suffers from large NDZ, meaning small power mismatches may not cause sufficient deviations in the
voltage to exceed the corresponding thresholds. The UOV- and UOF-based
IDMs generally suffer from a high nuisance detection ratio. Therefore, these
passive IDMs are used as backup protection against unintentional islanding
[53], [62], [81].

2.2.1.2 Rate of Change of Voltage

The ROCOV can be used to detect islanding conditions as the variations of
the PCC voltage during islanding are typically larger than normal [30], [37],
[82]. However, non-islanding events such as motor starting and capacitor
bank switching can also cause the ROCOV to exceed the threshold and lead
to nuisance detection [14].

2.2.1.3 Rate of Change of Frequency

The ROCOF has been widely utilized for passive islanding detection. Upon
islanding, the generation-load power imbalance causes frequency deviation
and leads to a large ROCOF. Protective relays operating based on the ROCOF
measure the time derivative of frequency over a few cycles to detect islanding
[30], [62], [83]. This method requires a generation-load power mismatch of
more than 15% to reliably detect islanding [81], [84], [85] and may suffer
from low detection speed [57], [86], [87].
2.2.1.4 Rate of Change of Power

After an islanding incident, the ROCOP measured by each DER at its terminal is typically greater than the ROCOP under normal conditions. Islanding can be detected when the rate of change of the DER output power exceeds a threshold [80], [88]. A disadvantage of the ROCOP-based IDM is that it may cause nuisance detection if the DER output power changes too fast under normal operating conditions [81].
2.2.2 Signal Processing-Based IDMs

A group of passive IDMs utilize signal processing techniques to extract features from power system variables, e.g., voltage, frequency, and ROCOF, that can be used for the detection of islanding. The most commonly used signal processing tools are the wavelet transform, S-transform, and Hilbert Huang transform (HHT) [39], [73]. These techniques are briefly discussed below.

The wavelet transform is a linear transformation similar to the Fourier transform but with better time-localization of signal frequency components. This technique has been utilized in a variety of power system applications [89]. The wavelet transform-based IDM extracts the energy coefficients of the power system signals. It detects islanding if the extracted energy coefficients exceed certain thresholds. Wavelet suffers from a high computational burden and noise sensitivity [81].

An extension of the concept of the wavelet transform is S-transform [39], [90]. In [91] a method using wavelet transform and S-transform is proposed to extract features for the detection of islanding and power quality disturbances. The findings of [92], [93] indicate that the performance of the wavelet transform degrades considerably under noisy situations, while S-transform...
can perform reliably under both noise-free and noisy conditions. A disadvantage of the S-transform is that its performance degrades under certain conditions such as power system transients [73], [94], [95].

The HHT is a powerful signal processing tool that is developed based on empirical mode decomposition and Hilbert transform [96]. The advantages of the HHT as a robust signal processing technique over the wavelet transform and S-transform have been demonstrated in the literature [97]–[100]. The findings of [101] indicate that the HHT can be utilized for islanding detection with a small NDZ and is applicable to multi-DER systems. However, HHT requires a long time to process a signal [102].

Mathematical morphology is a relatively simple signal processing technique based on the addition and subtraction of signals [73], [103]. The studies reported in [104], [105] indicate that mathematical morphology enables fast islanding detection under a variety of operating conditions, e.g., noise. However, this method tends to remove important features from noisy data along with the noise [106].
The auto-correlation function (ACF) is a signal processing technique that represents the correlation between a signal and its delayed version, which is used to extract hidden information from signals [39], [107]. ACF is used in [107], [108], and the results show that it leads to a small NDZ. As compared to other signal processing-based IDM\(\text{s}, \) ACF is computationally efficient. However, it may lead to false detection of non-islanding events [109].

The Kalman filter is a famous time-frequency domain signal processing technique that has been used to extract features such as harmonics from power system signals [39], [47]. The results of the studies conducted on the application of the Kalman filter for islanding detection as well as other power system applications indicate that this method performs reliably in noisy environments and is less sensitive to harmonics as compared to wavelet transform [47], [110]–[112]. However, the Kalman filter is complex and computationally expensive [113].
2.2.3 Artificial Intelligence-Based IDMs

There are difficulties associated with the threshold selection for conventional and signal processing-based passive IDMs. If the threshold is chosen with a large safety margin, the IDM becomes less sensitive and may fail to detect islanding. If the threshold is chosen without a sufficient safety margin, the IDM becomes too sensitive and may cause nuisance detection. Artificial intelligence-based IDMs operate based on various system parameters, e.g., voltage, frequency, ROCOF, and ROCOP, that can indicate islanding, without requiring the user to determine the thresholds [30], [73], [81]. These IDMs discriminate islanding from other operating conditions through pattern recognition and event classification. There are several intelligent classifiers such as artificial neural network (ANN) [114]–[118], probabilistic neural network (PNN) [119], [120], artificial immune system [121], [122], decision tree [123]–[126], and fuzzy logic [127]–[131], which are employed to rapidly detect islanding. The most common techniques are discussed below.

As one of the most widely used intelligent classifiers for power system applications, ANNs consist of input, hidden, and output layers with connected neurons, as shown in Figure 2.2. ANNs mimic the behaviour of the human brain. It is shown in [30], [117] that the ANN can detect islanding with high
speed even when the load quality factor $Q_f$ is large. In [132], ANN is used for fast islanding detection with high accuracy. However, ANN has certain disadvantages. The learning process may not achieve a high accuracy due to the multi-modal nature of the data. Furthermore, the generalizability of the ANN-IDM is a concern because its performance relies on the utilized neural network architecture.

![Structure of an artificial neural network.](image)

Figure 2.2: Structure of an artificial neural network.
The PNN is a type of neural network with fast training capability that is essentially developed based on the Bayesian function. The PNN classifier is utilized in [133] for islanding detection, where the features extracted by wavelet transform are fed to a PNN classifier for the detection of islanding events. An average accuracy of 89.76% is achieved which is too low. PNNs generally require more computational resources and time than ANNs.

The decision tree is another intelligent classification technique that can break a complex decision-making process into several simpler decisions by using splitting criteria [134], [135]. As shown in Figure 2.3, the splits are made on decision nodes based on splitting criteria. A leaf node is where no more splits are made. The decision tree classifier and the wavelet transform have been used together in [124], which has led to an islanding detection accuracy of 98%. An advantage of decision trees as compared to other pattern recognition methods is a faster training process, but it has limitations such as complexity and the dependence of the islanding detection threshold on the splitting criteria [30], [35], [39], [73].
Fuzzy logic is considered a promising tool for modelling ambiguity, uncertainty, and imprecision in a mathematical form [30]. In [131], the features extracted by S-transform are fed into a fuzzy rule-based classifier to detect islanding, where the average accuracy of 99.8% is achieved. An advantage of fuzzy rule-based classifiers as compared to decision trees is better interpretability [131]. However, it suffers from some shortcomings such as sensitivity to noise, lack of self-organization and self-tuning mechanisms, and a need for expert knowledge [30], [39], [129], [136].
2.3 Summary and Conclusions

The advantages and disadvantages of each category of IDMs are briefly outlined in part 1.1. All categories of IDMs have some advantages and disadvantages; there is no existing IDM that can outperform other methods in all performance indices and operate impeccably under all scenarios.

The main disadvantage of the conventional passive IDMs is their relatively large NDZ. To tackle the shortcomings associated with conventional passive IDMs, the application of signal processing and artificial intelligence in islanding detection has received significant attention. However, the challenges associated with their higher cost, computational burden, and noise sensitivity still need to be addressed.
The number of the research papers published between 1992-2021 is presented in Figure 2.4 which is obtained from the research information datasets available in IEEE Xplore\(^1\), Google Scholar\(^2\), and Dimensions\(^3\). The research trend in islanding detection studies suggest an encouraging future for passive IDMs.

![Figure 2.4: Number of the research papers published between 1992-2021 in each category of IDMs.](https://via.placeholder.com/150)

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\(^1\) [https://ieeexplore.ieee.org/search/advanced](https://ieeexplore.ieee.org/search/advanced)

\(^2\) [https://scholar.google.com/](https://scholar.google.com/)

\(^3\) [https://app.dimensions.ai/discover/publication](https://app.dimensions.ai/discover/publication)
Table 2 provides a high-level comparison of the passive, active, hybrid, and remote IDMs.

**Table 2: High-Level Comparison of Islanding Detection Methods.**

<table>
<thead>
<tr>
<th>Classification of IDMs</th>
<th>Principle of operation</th>
<th>NDZ</th>
<th>Detection speed</th>
<th>Effect on power quality</th>
<th>Cost</th>
<th>Applicability in multi-DER systems</th>
</tr>
</thead>
<tbody>
<tr>
<td>Passive</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Conventional Monitoring changes in system parameters</td>
<td>Large</td>
<td>High</td>
<td>None</td>
<td>Low</td>
<td>Preferred</td>
<td></td>
</tr>
<tr>
<td>Signal processing-based Feature extraction</td>
<td>Negligible</td>
<td>High</td>
<td>None</td>
<td>High</td>
<td>Preferred</td>
<td></td>
</tr>
<tr>
<td>Artificial intelligence-based Pattern recognition</td>
<td>Negligible</td>
<td>High</td>
<td>None</td>
<td>High</td>
<td>Preferred</td>
<td></td>
</tr>
<tr>
<td>Active</td>
<td>Perturbation</td>
<td>Small</td>
<td>Low</td>
<td>Highly degrades power quality</td>
<td>Medium</td>
<td>Not preferred</td>
</tr>
<tr>
<td>Hybrid</td>
<td>Combination of passive and active methods</td>
<td>Small</td>
<td>Medium</td>
<td>Degrades power quality</td>
<td>Medium</td>
<td>Not preferred</td>
</tr>
<tr>
<td>Remote</td>
<td>Communication b/w DER and utility</td>
<td>Zero</td>
<td>Medium</td>
<td>None</td>
<td>Very high</td>
<td>Preferred</td>
</tr>
</tbody>
</table>
Chapter 3

3 The Proposed Islanding Detection Method

Accurate detection of the frequency and phase angle of the grid voltage is one of the basic requirements for the interconnection of DERs with the utility grid, for which a PLL is widely used [137], [138]. Typically, a PLL consists of three components, namely a phase detector, a loop filter, and a digitally controlled oscillator [139]–[141]. The main difference among the PLLs is in the implementation of the phase detector [140]–[142].

Synchronous reference frame (SRF) PLLs which use DQ transformation as the phase detector [141] are widely utilized in three-phase systems [138], [140], [141]. Figure 3.1 shows the structure of the SRF PLL. The three-phase voltages measured at the PCC undergo DQ transformation in a rotating frame which results in the following signals:

\[
V_d = \frac{2}{3} (v_a \sin(\omega't) + v_b \sin(\omega't - 2\pi/3) + v_c \sin(\omega't + 2\pi/3)) \tag{6}
\]

\[
V_q = \frac{2}{3} (v_a \cos(\omega't) + v_b \cos(\omega't - 2\pi/3) + v_c \cos(\omega't + 2\pi/3)) \tag{7}
\]
where $v_a$, $v_b$, and $v_c$ are the PCC instantaneous voltages of phase $a$, $b$, and $c$ respectively, and $\omega'$ is the frequency tracked by the PLL. The lock is realized by controlling the q-axis component of voltage ($V_q$), i.e., the PLL error to be zero, which is achieved using a PI regulator.

![Structure of the SRF PLL.](image)

Figure 3.1: Structure of the SRF PLL.

In [141], a quasi-static PLL model is proposed which can be used for the analysis of the PLL behaviour in an islanded system. The quasi-static model consists of the self synchronization loop and the grid synchronization loop, as shown in Figure 3.2. In this model, $V_{grid}$ is the grid voltage amplitude, $I_{inv}$ is the inverter current amplitude reference, and $\phi_{inv}(\omega')$ is the phase shift angle due to the presence of the reactive components in the local load and the grid impedance, as shown in (8) [141].

$$\phi_{inv}(\omega') = \angle \left( \frac{z_L(\omega')z_g(\omega')}{z_L(\omega') + z_g(\omega')} \right)$$

(8)
In (8), $z_L(\omega')$ and $z_g(\omega')$ are the local load equivalent impedance and the grid impedance both at the tracked frequency, respectively.

Figure 3.2: Quasi-static PLL model.

The parameters $K_1$ and $K_2$ can be expressed as [141]:

$$K_1 = \frac{z_L(\omega)}{z_L(\omega) + z_g(\omega)} \quad (9)$$

$$K_2 = \frac{z_L(\omega')z_g(\omega')}{z_L(\omega') + z_g(\omega')} \quad (10)$$

where $\omega$ is the grid frequency and $z_L(\omega)$ and $z_g(\omega)$ are the local load equivalent impedance and the grid impedance both at the grid frequency, respectively.
As soon as islanding occurs, due to loss of grid synchronization, the PLL goes through self synchronization. The self synchronization loop tends to drive $\theta'$ away from the PCC phase angle $\theta$. From (8), it can be concluded that in a stiff grid-connected system ($z_g = 0$), $\varphi_{inv}(\omega')$ becomes zero, and the self synchronization loop disappears.

In a practical grid-connected system, the grid synchronization loop adjusts the input error $\theta - \theta'$ such that $v^-$ eliminates $v^+$ and $V_q$ becomes zero. Upon islanding, the grid synchronization loop disappears and $V_q$ steps from zero to $v^+$. Based on (8) and (10), the value of $v^+$ after islanding ($z_g = \infty$) becomes:

$$v^+ = |z_L(\omega')| I_{inv} \sin(\angle z_L(\omega')) \quad (11)$$

Subsequently, the inverter voltage and frequency approach different values corresponding to a new equilibrium determined by power mismatches [143].
Considering the PLL behaviour, this thesis introduces a passive IDM that operates based on the variations of the $V_q$. The maximum post-islanding value of $V_q$ can be determined using (11) for any system, based on the total equivalent load impedance and the maximum inverter current magnitude. Hence, an appropriate value for the $Vq$ threshold can be systematically determined based on the information of the equivalent load and inverter. Figure 3.3 shows a flowchart of the proposed algorithm. A second-order lowpass Butterworth filter with a cut-off frequency of 100 Hz, and a 3 ms timer are utilized to prevent false detection of non-islanding surges or malfunction due to the presence of noise in the system. The 3 ms timer is chosen such that the adverse effect of high-frequency disturbances is mitigated without unnecessary prolongation of islanding detection.
Figure 3.3: Flowchart of the proposed IDM.
Chapter 4

4 Performance Evaluation

This chapter investigates the performance of the proposed passive IDM under several operating conditions and compares it with those of the most commonly used passive IDMs through various islanding and non-islanding disturbances. The studies include time-domain simulations in the PSCAD/EMTDC software environment and experimental tests conducted using the hybrid microgrid test platform of Figure 1.4.

The operating quantities obtained from measurements conducted on the hybrid microgrid test platform are post-processed in Matlab.
4.1 Islanding

The performance of the passive IDMs under an islanding event is investigated and compared through simulation studies conducted on the study system 1, and experimental tests using the study system 3.

For both simulation and hardware implementation of the investigated methods, the thresholds are chosen such that a compromise is made between islanding detection speed and reliability. An exception is UOV- and UOF-based IDMs, for which it is widely practiced to adapt the thresholds to the voltage and frequency requirements of IEEE 1547\textsuperscript{1}.

Figure 4.1 shows the variations of different operating quantities utilized for passive islanding detection under an islanding event in study system 1, at $t = 0.2 \, s$.

The experimental results representing the variations of different operating quantities under an islanding event in study system 3, at $t = 0.2 \, s$, are presented in Figure 4.2.

\textsuperscript{1} Refer to Table 1.
Figure 4.1: Variations of different operating quantities utilized for passive islanding detection under an islanding event in the study system 1, at $t = 0.2 \text{ s}$ (simulation results): (a) PCC voltage magnitude, (b) frequency, (c) ROCOV, (d) ROCOF, (e) ROCOP, and (f) $q$-axis voltage $V_q$. 
Figure 4.2: Variations of different operating quantities utilized for passive islanding detection under islanding event in the study system 3, at $t = 0.2 \text{ s}$ (experimental results): (a) PCC voltage magnitude, (b) frequency, (c) ROCOF, (d) ROCOV, (e) ROCOP, and (f) q-axis voltage $V_q$. 
4.1.1 Non-Detection Zone

The study system 2 is utilized to evaluate the NDZ of the IDMs. The equivalent parallel RLC load is calculated according to the requirements of IEEE 1547 for the worst scenario, i.e., zero power mismatch between the DER output and load, as well as $\pm 5\%$, $\pm 10\%$, and $\pm 15\%$ mismatch in both active and reactive powers. A positive mismatch indicates power surplus and a negative mismatch indicates power deficit. The load quality factor $Q_f$ is assumed to be equal to 1, as recommended by the IEEE 1547 standard.

Figure 4.3 shows the variations of the operating parameters under an islanding event in the study system 2 at $t = 0.2\, s$, considering a $-15\%$ active and reactive power mismatch. The ROCOV-, ROCOF-, and ROCOP-based IDMs fail to detect the islanding event.

Figure 4.4 compares the IDMs considering a $+15\%$ power mismatch. In this case, only the UOF-based and the proposed IDM detect the islanding event. Also, the ROCOF-based IDM comes very close to the threshold which confirms that ROCOF-based islanding detection may lead to an NDZ of about 15\% \cite{56,81,84,85}.

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1 Refer to 1.5.2 for the description.
Figure 4.3: Variations of different operating quantities utilized for passive islanding detection under an islanding event in the study system 2, at $t = 0.2 \, s$, considering a $-15\%$ power mismatch (simulation results): (a) PCC voltage magnitude, (b) frequency, (c) ROCOV, (d) ROCOF, (e) ROCOP, and (f) q-axis voltage $V_q$. 

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Figure 4.4: Variations of different operating quantities utilized for passive islanding detection under an islanding event in the study system 2, at $t = 0.2$ s, considering a +15% power mismatch (simulation results): (a) PCC voltage magnitude, (b) frequency, (c) ROCOV, (d) ROCOF, (e) ROCOP, and (f) q-axis voltage $V_q$. 
Figure 4.5 shows the variations of the operating parameters under an islanding event in study system 2 at \( t = 0.2 \, \text{s} \), considering a \(-10\%\) active and reactive power mismatch. As shown in Figure 4.5 (b) and (f), the UOF-based method and the proposed IDM detect the islanding event. Figure 4.6 shows the zoomed-in variations of the voltage magnitude and the generated islanding detection signal (IDS). The voltage magnitude crosses the lower threshold for not a sufficiently long period to generate a pulse, meaning the UOV-based IDM fails to reliably detect islanding.

The variations of the operating parameters under an islanding event in the study system 2 at \( t = 0.2 \, \text{s} \), considering a \(+10\%\) active and reactive power mismatch, are provided in Figure 4.7. Figure 4.7 (b) and (f) illustrate that only the UOF-based and the proposed IDM can detect the islanding event.
Figure 4.5: Variations of different operating quantities utilized for passive islanding detection under an islanding event in the study system 2, at $t = 0.2 \text{ s}$, considering a $-10\%$ power mismatch (simulation results): (a) PCC voltage magnitude, (b) frequency, (c) ROCOV, (d) ROCOF, (e) ROCOP, and (f) q-axis voltage $V_q$. 
Figure 4.6: Variations of voltage magnitude under an islanding event considering a $-10\%$ power mismatch (left) and the generated IDS (right), zoomed-in version of Figure 4.5 (a).
Figure 4.7: Variations of different operating quantities utilized for passive islanding detection under an islanding event in the study system 2, at $t = 0.2 \text{s}$, considering a +10\% power mismatch (simulation results): (a) PCC voltage magnitude, (b) frequency, (c) ROCOV, (d) ROCOF, (e) ROCOP, and (f) q-axis voltage $V_q$. 
Figure 4.8 illustrates the variations of the operating parameters under an islanding event in study system 2 at $t = 0.2$ s, considering $-5\%$ active and reactive power mismatch. Figure 4.8 (f) shows that the proposed IDM detects the islanding event. Figure 4.9 presents a closer look into the variations of the frequency, which indicates successful islanding detection.

Figure 4.10 shows the variations of the operating parameters under an islanding event in the study system 2 at $t = 0.2$ s, considering $+5\%$ active and reactive power mismatch. In this case, the UOF-based IDM can detect islanding as shown in Figure 4.10 (b). A zoomed-in version of Figure 4.10 (f) is provided in Figure 4.11, which shows that $V_q$ exceeds the threshold for longer than the 3 ms delay. Therefore, the proposed IDM successfully detects the islanding event considering a $+5\%$ power mismatch.
Figure 4.8: Variations of different operating quantities utilized for passive islanding detection under an islanding event in the study system 2, at $t = 0.2 \text{ s}$, considering a $-5\%$ power mismatch (simulation results): (a) PCC voltage magnitude, (b) frequency, (c) ROCOV, (d) ROCOF, (e) ROCOP, and (f) q-axis voltage $V_q$. 
Figure 4.9: Variations of frequency under an islanding event considering a $-5\%$ power mismatch (left) and the generated IDS (right), zoomed-in version of Figure 4.8 (b).
Figure 4.10: Variations of different operating quantities utilized for passive islanding detection under an islanding event in the study system 2, at $t = 0.2 \, s$, considering a +5% power mismatch (simulation results): (a) PCC voltage magnitude, (b) frequency, (c) ROCOV, (d) ROCOF, (e) ROCOP, and (f) q-axis voltage $V_q$. 
Figure 4.11: Variations of q-axis voltage $V_q$ under an islanding event considering a $\pm 5\%$ power mismatch (left) and the generated IDS (right), zoomed-in version of Figure 4.10 (f).

Finally, Figure 4.12 compares the performance of the investigated IDMs for 0\% active and reactive power mismatches. As expected, none of the IDMs can detect the occurrence of islanding in this case due to the inherent limitation of all passive IDMs.
Figure 4.12: Variations of different operating quantities utilized for passive islanding detection under an islanding event in the study system 2, at \( t = 0.2 \) s, considering a 0% power mismatch (simulation results): (a) PCC voltage magnitude, (b) frequency, (c) ROCOV, (d) ROCOF, (e) ROCOP, and (f) q-axis voltage \( V_q \).
Table 3 summarizes the simulation results obtained from NDZ studies conducted on the study system 2 under different power mismatch scenarios. The UOF-based and the proposed method operate reliably under power mismatches as small as ±5%. However, none of them can detect islanding in case of perfect power balance. It should be noted that in practice, there is always some power mismatch between the DER output and the load [48].

Table 3: NDZ of the Investigated IDMs.

<table>
<thead>
<tr>
<th>Power Mismatch (%)</th>
<th>Performance</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>UOV</td>
</tr>
<tr>
<td>+15</td>
<td>Failed</td>
</tr>
<tr>
<td>+10</td>
<td>Failed</td>
</tr>
<tr>
<td>+5</td>
<td>Failed</td>
</tr>
<tr>
<td>0</td>
<td>Failed</td>
</tr>
<tr>
<td>-5</td>
<td>Failed</td>
</tr>
<tr>
<td>-10</td>
<td>Failed</td>
</tr>
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<td>-15</td>
<td>✓</td>
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</tbody>
</table>
4.1.2 Detection Time

Table 4 presents the detection time of each IDM based on the results of the islanding studies conducted on the study system 1, study system 2, and study system 3.

Table 4: Detection Time of the Investigated IDMs.

<table>
<thead>
<tr>
<th>Detection Time (ms)</th>
<th>Simulation</th>
<th>Experimental</th>
<th>Average Detection Time</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Study System 1(^1)</td>
<td>Study System 2 (30% power deficit)</td>
<td>Study System 3(^2)</td>
</tr>
<tr>
<td>UOV</td>
<td>7</td>
<td>9</td>
<td>4</td>
</tr>
<tr>
<td>UOF</td>
<td>22</td>
<td>13</td>
<td>9</td>
</tr>
<tr>
<td>ROCOV</td>
<td>11</td>
<td>10</td>
<td>7</td>
</tr>
<tr>
<td>ROCOF</td>
<td>38</td>
<td>18</td>
<td>58</td>
</tr>
<tr>
<td>ROCOP</td>
<td>22</td>
<td>11</td>
<td>8</td>
</tr>
<tr>
<td>Proposed IDM</td>
<td>22</td>
<td>7</td>
<td>24</td>
</tr>
</tbody>
</table>

---

\(^1\) Refer to Appendix A for the load specifications.

\(^2\) Refer to Appendix B for the load specifications.
As shown in Table 4, the UOV- and ROCOV-based IDMs with detection times of less than one cycle, are the fastest among the investigated IDMs, and ROCOF with a detection time of around three cycles is the slowest method. The detection time of the proposed IDM is less than 2 cycles.

As per IEEE 1547-2018, a DER is required to detect islanding, discontinue to energize the system, and trip within 2 s of the formation of an island. Of course, this requirement is not strict and a faster islanding detection is desirable. The detection time of the proposed IDM is well below the requirements of IEEE 1547.
4.2 Non-Islanding Disturbances

4.2.1 Fault ‘F1’

In this case study, a single-phase-to-ground fault ‘F1’ (Figure 1.2), with a fault resistance $R_f = 0.01 \, \Omega$ occurs in the study system 1 at $t = 0.2 \, s$. Figure 4.13 shows the variations of different operating quantities utilized for passive islanding detection.

As shown in Figure 4.13 (a), the UOV-based IDM misidentifies fault ‘F1’ as islanding. Figure 4.14 represents a zoomed-in version of Figure 4.13 (b) and the generated IDS, which indicates that the UOF-based IDM also detects ‘F1’ as islanding.
Figure 4.13: Variations of different operating quantities utilized for passive islanding detection under fault ‘F1’ in the study system 1, at $t = 0.2$ s (simulation results): (a) PCC voltage magnitude, (b) frequency, (c) ROCOV, (d) ROCOF, (e) ROCOP, and (f) q-axis voltage $V_q$. 
4.2.2 Fault ‘F2’

In this case study, a single-phase-to-ground fault ‘F2’ (as shown in Figure 1.2), with a fault resistance $R_f = 0.01 \, \Omega$ occurs in the study system 1 at $t = 0.2 \, s$. Figure 4.15 shows the variations of different operating quantities utilized for passive islanding detection.

Figure 4.15 (c) and (e) show that the ROCOV and ROCOP come very close to the thresholds, however, do not cause false detection. Figure 4.15 (a) shows that the UOV-based IDM detects ‘F2’ as islanding.
Figure 4.15: Variations of different operating quantities utilized for passive islanding detection under fault ‘F2’ in study system 1, at $t = 0.2$ s (simulation results): (a) PCC voltage magnitude, (b) frequency, (c) ROCOV, (d) ROCOF, (e) ROCOP, and (f) q-axis voltage $V_q$. 
4.2.3 Motor Starting

In this case study, a 4.8 kV, 1.7 MVA motor (Figure 1.2) is started in the study system 1 at $t = 0.2 \, \text{s}$. Figure 4.16 shows the variations of different operating quantities utilized for passive islanding detection during motor starting. In this case, the voltage magnitude experiences the largest deviation, however, none of the IDMs misidentifies this disturbance.

The study system 3 is utilized to experimentally evaluate the performance of the IDMs under motor starting. A three-phase 15 W induction motor connected to bus 3 (Figure 1.4) is started at $t = 0.2 \, \text{s}$. Figure 4.17 (d) shows that the ROCOV-based IDM misidentifies this disturbance. As Figure 4.17 (a) illustrates, the UOV-based IDM comes very close to its lower threshold. However, as shown in Figure 4.18, it does not lead to nuisance detection.
Figure 4.16: Variations of different operating quantities utilized for passive islanding detection under motor starting in the study system 1, at $t = 0.2 \text{ s}$ (simulation results): (a) PCC voltage magnitude, (b) frequency, (c) ROCOV, (d) ROCOF, (e) ROCOP, and (f) q-axis voltage $V_q$. 
Figure 4.17: Variations of different operating quantities utilized for passive islanding detection under motor starting in the study system 3, at \( t = 0.2 \text{s} \) (experimental results): (a) PCC voltage magnitude, (b) frequency, (c) ROCOF, (d) ROCOV, (e) ROCOP, and (f) q-axis voltage \( V_q \).
Figure 4.18: Variations of voltage magnitude under motor starting (left) and the generated IDS (right), zoomed-in version of Figure 4.17 (a).
4.2.4 Static Load Switching

In this case study, a 1000 kW, 1000 kVAR static load (load #16 in Figure 1.2) is switched on in the study system 1, at $t = 0.2\, s$. The variations of the operating parameters under the event of load switching are illustrated in Figure 4.19, which does not show any false detection of the disturbance as islanding.

The study system 3 is utilized to experimentally evaluate the performance of the IDMs under the static load switching event. In this case, a 30 W AC load (AC-L3 in Figure 1.4) is switched on at $t = 0.2\, s$. Figure 4.20 (d) shows that the ROCOV exceeds the lower threshold which indicates false detection of the disturbance as islanding. Even though the voltage magnitude does not exceed the threshold in Figure 4.20 (a), it is prone to nuisance detection.
Figure 4.19: Variations of different operating quantities utilized for passive islanding detection under static load switching in the study system 1, at $t = 0.2$ s (simulation results): (a) PCC voltage magnitude, (b) frequency, (c) ROCOV, (d) ROCOF, (e) ROCOP, and (f) q-axis voltage $V_q$. 
Figure 4.20: Variations of different operating quantities utilized for passive islanding detection under static load switching in the study system 3, at $t = 0.2 \, \text{s}$ (experimental results): (a) PCC voltage magnitude, (b) frequency, (c) ROCOF, (d) ROCOV, (e) ROCOP, and (f) q-axis voltage $V_q$. 
4.2.5 Nuisance Detection

The results of the non-islanding case studies from study systems 1 and 3 are compared and summarized in Table 5. As shown in the table, the ROCOF-based, ROCOP-based, and the proposed IDM do not cause false detection (FD), therefore, they show better security against the investigated non-islanding scenarios.

<table>
<thead>
<tr>
<th></th>
<th>Study system 1</th>
<th></th>
<th>Study system 3</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(Simulation Results)</td>
<td></td>
<td>(Experimental Results)</td>
</tr>
<tr>
<td>Fault</td>
<td>Motor starting</td>
<td>Static load switching</td>
<td>Motor starting</td>
</tr>
<tr>
<td>F1</td>
<td>F2</td>
<td></td>
<td>UOV</td>
</tr>
<tr>
<td></td>
<td>UOF</td>
<td></td>
<td>FD</td>
</tr>
<tr>
<td>ROCOV</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>ROCOF</td>
<td>-</td>
<td>-</td>
<td>FD</td>
</tr>
<tr>
<td>ROCOP</td>
<td>-</td>
<td>-</td>
<td>FD</td>
</tr>
<tr>
<td>Proposed IDM</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>
Chapter 5

5 Conclusions

5.1 Conclusions

A novel passive IDM is introduced in this thesis. The proposed IDM utilizes an internal parameter of PLL, namely the q-axis component of voltage $V_q$, as an indicator of islanding. Upon islanding, $V_q$ suddenly increases, and by applying an appropriate threshold, islanding can be detected quickly and reliably.

Similar to other passive IDMs, the proposed IDM does not degrade power quality or adversely affect the power system stability, as it does not require external signal injection. Also, it can be applied to multi-DER systems like study system 1 which comprises PV, WT and energy storage units. In addition, the proposed IDM is cost-effective; it does not require expensive hardware for communication and only utilizes the parameter obtained from an already-existing PLL.

The proposed method can detect islanding with an average time delay of 18 ms, which is well below the requirements of the IEEE 1547 standard. It
benefits from a small NDZ and can identify the islanding conditions in case of only ±5% power mismatch. Only the UOF-based IDM provides similar dependability, however, it shows low security against the investigated non-islanding events. The proposed IDM does not falsely detect non-islanding disturbances, and it provides the highest reliability among the investigated passive IDMs.

The competency of the proposed IDM is verified using multiple studies conducted on the realistic model of a Canadian rural distribution network as well as the IEEE recommended test system in the PSCAD software environment. Furthermore, the efficacy of the proposed IDM has been experimentally validated using a hybrid microgrid test platform.
5.2 Future Work

Although this study is focused on the detection of islanding using the variations of the q-axis component of voltage $V_q$, the effect of the PLL parameters on the proposed IDM can be investigated. The continuation of this study in the future includes analysis of the effect of PLL design on the performance of the proposed method.

The future work also includes investigating the performance of the proposed method using a wider range of study systems and the recorded signals of real-world islanding events.
References


[29] V. R. Reddy and E. S. Sreeraj, “A Feedback-Based Passive Islanding Detection Technique for One-Cycle-Controlled Single-Phase Inverter Used in Photovoltaic


## Appendices

### Appendix A: Study System 1 Parameters

The general parameters, line lengths, and load specifications of study system 1 are provided in the tables below.

Table A.1: General System Parameters – Study System 1.

<table>
<thead>
<tr>
<th>Component</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grid</td>
<td>$V_{LL-base} = 27.6$ kV, 60 Hz</td>
</tr>
<tr>
<td></td>
<td>$S_{nom} = 20$ MVA, SSC = 885.33, X/R = 10</td>
</tr>
<tr>
<td>Wind power plant</td>
<td>$S_{WT} = 4$ MVA = 2×2 MVA</td>
</tr>
<tr>
<td>PV power plant</td>
<td>$S_{PV} = 3.5$ MVA</td>
</tr>
<tr>
<td>BESS units</td>
<td>$S_{BESS} = 2×2$ MVA</td>
</tr>
<tr>
<td>Transformers</td>
<td>T1: 3.6 MVA, 6% impedance, 27.6 kV/8.31 kV, $\Delta Y$</td>
</tr>
<tr>
<td></td>
<td>T2: 15 MVA, 7.3% impedance, 27.6 kV/27.6 kV, YY</td>
</tr>
<tr>
<td></td>
<td>T3: 1 MVA, 4% impedance, 27.6 kV/8.31 kV, $\Delta Y$</td>
</tr>
<tr>
<td></td>
<td>T4: 3.6 MVA, 5.65% impedance, 27.6 kV/8.31 kV, $\Delta Y$</td>
</tr>
<tr>
<td>Overhead lines</td>
<td>Spacing ID = STD-3PH-NBP, $R_1 = 0.172$ Ω/km, $R_0 = 0.491$ Ω/km,</td>
</tr>
<tr>
<td></td>
<td>$X_1 = 0.404$ Ω/km, $X_0 = 1.354$ Ω/km,</td>
</tr>
<tr>
<td></td>
<td>$B_1 = 4.171$ uS/km, $B_0 = 1.759$ uS/km</td>
</tr>
</tbody>
</table>
Table A.2: Overhead Lines Lengths – Study System 1.

<table>
<thead>
<tr>
<th>Line</th>
<th>Length (m)</th>
<th>Line</th>
<th>Length (m)</th>
<th>Line</th>
<th>Length (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>L1</td>
<td>5700</td>
<td>L11</td>
<td>3330</td>
<td>L21</td>
<td>1550</td>
</tr>
<tr>
<td>L2</td>
<td>1010</td>
<td>L12</td>
<td>1030</td>
<td>L22</td>
<td>2120</td>
</tr>
<tr>
<td>L3</td>
<td>400</td>
<td>L13</td>
<td>3490</td>
<td>L23</td>
<td>1820</td>
</tr>
<tr>
<td>L4</td>
<td>380</td>
<td>L14</td>
<td>1430</td>
<td>L24</td>
<td>2540</td>
</tr>
<tr>
<td>L5</td>
<td>120</td>
<td>L15</td>
<td>190</td>
<td>L25</td>
<td>620</td>
</tr>
<tr>
<td>L6</td>
<td>170</td>
<td>L16</td>
<td>1940</td>
<td>L26</td>
<td>3580</td>
</tr>
<tr>
<td>L7</td>
<td>260</td>
<td>L17</td>
<td>2450</td>
<td>L27</td>
<td>770</td>
</tr>
<tr>
<td>L8</td>
<td>140</td>
<td>L18</td>
<td>1630</td>
<td>L28</td>
<td>2080</td>
</tr>
<tr>
<td>L9</td>
<td>940</td>
<td>L19</td>
<td>1200</td>
<td>L29</td>
<td>4510</td>
</tr>
<tr>
<td>L10</td>
<td>300</td>
<td>L20</td>
<td>820</td>
<td>L30</td>
<td>4040</td>
</tr>
</tbody>
</table>
Table A.3: Load Specifications – Study System 1\textsuperscript{1}.

<table>
<thead>
<tr>
<th>Load #</th>
<th>Three Phase KVA</th>
<th>Power Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2364</td>
<td>0.95</td>
</tr>
<tr>
<td>2</td>
<td>346</td>
<td>0.87</td>
</tr>
<tr>
<td>3</td>
<td>3355</td>
<td>0.95</td>
</tr>
<tr>
<td>4</td>
<td>256</td>
<td>0.75</td>
</tr>
<tr>
<td>5</td>
<td>6.3</td>
<td>1</td>
</tr>
<tr>
<td>6</td>
<td>265</td>
<td>0.95</td>
</tr>
<tr>
<td>7</td>
<td>650</td>
<td>1</td>
</tr>
<tr>
<td>8</td>
<td>50</td>
<td>0.95</td>
</tr>
<tr>
<td>9</td>
<td>160</td>
<td>0.95</td>
</tr>
<tr>
<td>10</td>
<td>205</td>
<td>1</td>
</tr>
<tr>
<td>11</td>
<td>445</td>
<td>0.95</td>
</tr>
<tr>
<td>12</td>
<td>10</td>
<td>0.95</td>
</tr>
<tr>
<td>13</td>
<td>215</td>
<td>0.95</td>
</tr>
<tr>
<td>14</td>
<td>85</td>
<td>0.95</td>
</tr>
<tr>
<td>15</td>
<td>110</td>
<td>0.95</td>
</tr>
</tbody>
</table>

\textsuperscript{1} Load #16 is a special load described in part 4.2.4 and does not exist in the original system.
Appendix B: Study System 3 Parameters

The general parameters, load specifications, and parameters of the hardware-implemented converters of study system 3 are provided in the tables below.

Table A.4: General System Parameters – Study System 3.

<table>
<thead>
<tr>
<th>Transformer</th>
<th>750 VA, 7% impedance,</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>208 V/160 V, YY</td>
</tr>
<tr>
<td>L1</td>
<td>$R = 25 , \text{m\Omega}, L = 56 , \mu\text{H}, C = 20 , \text{nF}$</td>
</tr>
<tr>
<td>L2</td>
<td>$R = 50 , \text{m\Omega}, L = 120 , \mu\text{H}, C = 33 , \text{nF}$</td>
</tr>
<tr>
<td>L3</td>
<td>$R = 25 , \text{m\Omega}, L = 120 , \mu\text{H}, C = 0.56 , \text{nF}$</td>
</tr>
<tr>
<td>L4</td>
<td>$R = 10 , \text{m\Omega}, L = 176 , \mu\text{H}, C = 1.2 , \text{nF}$</td>
</tr>
<tr>
<td>L5</td>
<td>$R = 50 , \text{m\Omega}, L = 200 , \mu\text{H}, C = 1 , \text{nF}$</td>
</tr>
</tbody>
</table>

Table A.5: Load Specifications – Study System 3.

| DC-L1       | 10 W DC   |
| DC-L2       | 10 W DC   |
| AC-L1       | 10 W AC   |
| AC-L2       | 10 W AC   |
| AC-L3       | 30 W AC   |
Table A.6: DC/DC Converter Specifications – Study System 3.

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rated power</td>
<td>80 W</td>
</tr>
<tr>
<td>Rated input DC voltage</td>
<td>40 V</td>
</tr>
<tr>
<td>Filter inductance</td>
<td>150.0 µH</td>
</tr>
<tr>
<td>DC filter capacitance</td>
<td>20 µF</td>
</tr>
<tr>
<td>Switching frequency</td>
<td>48 kHz</td>
</tr>
</tbody>
</table>

Table A.7: AC/DC VSC Specifications – Study System 3.

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rated power</td>
<td>90 W</td>
</tr>
<tr>
<td>Rated DC link voltage</td>
<td>40 V</td>
</tr>
<tr>
<td>LCL filter inverter-side inductance</td>
<td>300 µH</td>
</tr>
<tr>
<td>LCL filter capacitance</td>
<td>50 µF</td>
</tr>
<tr>
<td>LCL filter grid-side inductance</td>
<td>21.7 µH</td>
</tr>
<tr>
<td>LCL filter damping resistance</td>
<td>0.75 Ω</td>
</tr>
<tr>
<td>DC link filter capacitance</td>
<td>20 µF</td>
</tr>
<tr>
<td>Switching frequency</td>
<td>18 kHz</td>
</tr>
</tbody>
</table>

Table A.8: Battery Specifications.

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rated voltage</td>
<td>2×12 V DC</td>
</tr>
<tr>
<td>Capacity</td>
<td>2×10 Ah</td>
</tr>
</tbody>
</table>
Curriculum Vitae

Name: Hoda Zamani

Post-Secondary Education and Degrees:
Amirkabir University of Technology (Tehran Polytechnic)
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Honours and Awards:
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2022

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2019, 2015

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2019

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Western University
2016-2017, 2018-2019, 2021-now

Vice-president at Graduate Engineering Society (GES)
Western University
2021