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Review

Comprehensive Review of Islanding Detection Methods for Distributed Generation Systems

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Received: 31 December 2018; Accepted: 26 February 2019; Published: 4 March 2019

Abstract: The increased penetration of distributed generation (DG), renewable energy utilization, and the introduction of the microgrid concept have changed the shape of conventional electric power networks. Most of the new power system networks are transforming into the DG model integrated with renewable and non-renewable energy resources by forming a microgrid. Islanding detection in DG systems is a challenging issue that causes several protection and safety problems. A microgrid operates in the grid-connected or stand-alone mode. In the grid-connected mode, the main utility network is responsible for a smooth operation in coordination with the protection and control units, while in the stand-alone mode, the microgrid operates as an independent power island that is electrically separated from the main utility network. Fast islanding detection is, therefore, necessary for efficient and reliable microgrid operations. Many islanding detection methods (IdMs) are proposed in the literature, and each of them claims better reliability and high accuracy. This study describes a comprehensive review of various IdMs in terms of their merits, viability, effectiveness, and feasibility. The IdMs are extensively analysed by providing a fair comparison from different aspects. Moreover, a fair analysis of a feasible and economical solution in view of the recent research trend is presented.

Keywords: islanding detection; distributed generation; integrated power distribution network; non-detection zone; islanding detection method

1. Introduction

As the distributed generation (DG) industry continues its path of rapid growth and technological revolution, integrated power and energy networks are emerging as a fundamental enabling technology. With the increasing energy demands globally and fear of depleting conventional fossil fuels, the integration of DG networks has become essential [1]. The integration of DG systems with conventional power networks has primarily been increased by providing significant relief in the technical and commercial development. DG networks offer the benefits of producing reliable electricity onsite, thereby reducing the need to build new transmission lines and avoiding the line losses [2]. DG units offer significant assistance to power system consumers while adding flexibility to an electric grid based on the traditional centralized model [3]. These systems are used in applications ranging from residential to small commercial, and to industrial users. Due to the economic, environmental, and strategic benefits offered by renewable energy resources, the current energy market is significantly developed and moving towards decentralization [4].

In the microgrid system, DG units are categorized as voltage control, commonly termed as grid-forming, and current control, commonly termed as grid-following [5]. Usually, in the grid-connected operation, DG units are controlled as grid-following, while in an islanded operation, they are controlled as grid-forming. Therefore, the conventional control and protection strategies are not capable enough to handle the transfer of electrical power and manage several parallel operations [6]. Islanding operation is, therefore, critically studied and analysed by the researchers to present the best solutions for a technically coordinated operation of the microgrid and the main utility grid. Among the challenges associated with integrated power distribution networks (IPDNs), islanding detection is an essential and difficult task.

The influx of DG integration into the main utility networks is increasing rapidly. Besides the advantages, such influx may cause some abnormal conditions in case of regular electrical faults or common power system disturbances [7]. Such technical challenges are being resolved by professional engineers and researchers using advanced technologies and power economics. The DG units share the energy mix with the main utility grid to form an IPDN consisting of renewables, non-renewables, and energy storage systems [8]. An IPDN may operate in the grid-connected mode or islanded mode. If a DG unit and the main utility network are working in parallel to supply power to the load centres, the operation is known as a grid-connected mode [9]. In contrast, in the case of utility failure, the DG unit continues to supply power to the remaining load, and the operation is known as the islanded mode [10]. An islanding condition can be intentional or unintentional. Intentional islanding is performed due to the scheduled maintenance required for the main utility, whereas unintentional islanding may occur at any time due to regular faults or other uncertainties in the power system [11]. Therefore, islanding detection is considered as an important task for IPDNs. IEEE 1547 [12] and UL 1741 [13] standards describe DG interconnection, planned and unplanned power islanding, and other important operating considerations.

Unintentional islanding is a threat to power system security, which may cause damage to the utility operations, equipment, and maintenance workers. Hence, islanding in power networks is a big challenge for protection engineers. Unintentional power system islands may create overload conditions due to the suspended utility operation, which significantly impacts the voltage and frequency levels of DG units [14]. Additionally, in an islanding situation, the DG units are not capable enough to provide sufficient fault current in order to operate the conventional protection devices [15]. Such an islanding can damage the system equipment, affect power system reliability, and endanger the maintenance worker's life. The importance of islanding detection is highlighted by the fact that many international technical associations such as IEEE or IEC revise and modify the DG interconnection and islanding codes every two to three years [16]. As DG integration increases, the need for unintentional islanding detection will be more significant and challenging. Therefore, many new islanding detection methods (IdMs) have been developed to deal with these problems. Furthermore, the standards for intentional and unintentional islanding provide safe operational strategies and overcome the consequences of DG islanding, if properly implemented. For years, many IdMs have been presented, which reveal the fact that islanding is an open research problem. The following are the main contributions of this paper:

(1) A comprehensive review of various IdMs concerning their principle of operations, advantages and disadvantages, performance evaluation, and real-time applications is presented.
(2) A comparison of various IdMs in terms of accuracy, computational burden, speed, and cost is performed based on the critical analysis.
(3) An assessment of challenges in islanding detection in accordance with the guidelines recommended in well-known standards.
(4) Analysis of potential IdMs and identification of efficient schemes.
(5) Real-time applications of IdMs in AC and DC microgrids.

This paper presents a comprehensive review of various IdMs considering their performances and operational capabilities. Different classification and types of islanding detection schemes with a critical analysis, including their advantages and disadvantages, are discussed here. Moreover, several multiple approaches and analysing tools applied in existing IdMs are realized in a broad perspective. In light of the abovementioned framework, no detailed review on islanding detection is found in the literature. Therefore, the expected impact of this report is to provide a detailed perspective of islanding detection for integrated DG systems.

The outline of the review report is presented as follows: Section 2 describes the problem definition and future challenges pertaining to islanding detection and microgrid systems. In Section 3, a review of various islanding detection schemes is presented by highlighting their principle of operations and performances. The anti-islanding protection standards are discussed in Section 4. Section 5 describes the performance analysis of IdMs from the viewpoint of the non-detection zone (NDZ), parallel RLC load, and varying load quality factor. Section 6 provides a brief comparison of various IdMs, while Section 7 presents the recommendations and future research trends. Finally, Section 8 draws the conclusions of this study.

2. Problem Definition and Challenges

Unintentional islanding in power systems is a serious concern since the introduction of IPDN. These interconnected networks, along with inverter- and non-inverter-based DG systems, multiple load profiles, and a complex control mechanism possess a potential threat to the reliability of power system networks [17]. The history of mega blackouts and power system failures confirms the fact that the loss of utility has caused huge protection and economic crashes. Among these failures and losses, one of the main concerns is the formation of power system islanding. Many IdMs are available in the literature that utilize advanced mathematical and signal processing techniques as efficient capacity-building tools [18]. However, there are still certain challenges in the field of islanding detection that need to be investigated, such as the performance of IdMs for simultaneous events, i.e., fault followed by islanding for various DG systems, or the interaction among various DG systems equipped with anti-islanding protection when islanding occurs [19].

To address these challenges and highlight the sensitivity of anti-islanding protection, IdMs are critically analysed in this study. DG integration is becoming prevalent worldwide due to the increasing needs of power and energy, avoiding long transmission networks, or implementing resilient energy transitions [20]. However, many challenges in the form of operation, protection, and control from mega to micro level energy transition are running behind. A power system island, if unintentionally formed, creates trouble and severe damage to the utilizing equipment as well system operators. In the current scenario, the main concern of utility operators is to provide efficient and economic anti-islanding protection solutions for integrated AC and DC microgrid networks [21]. In addition, the researchers or analysts use various efficient models and management techniques to ensure well-secured and fast islanding detection operations for such networks.

3. Review of IdMs

IdMs are generally classified into two main groups: (a) local schemes and (b) remote schemes. Local schemes are further classified into active and passive schemes. Active schemes are generally based on the concept of perturb and observe technique [22], where an external signal is injected into the system, which perturbs the DG output parameters up to a significant level upon islanding occurrence. Under the grid-connected operation, the injected signal is not significantly distorted, but an effective change is observed in the system under the islanding condition. In passive schemes, islanding detection is achieved by observing significant deviations into the system's output parameters. The passive schemes may fail to detect the islanding condition when the load and DG power are balanced. Therefore, passive schemes possess a large NDZ. The performance of any IdM is evaluated on the basis of its NDZ. An NDZ represents the mismatch between the active and reactive powers generated by a DG unit and dissipated by a local load, for which the applied scheme will not be able to discriminate between the islanding and normal conditions [23].

The remote schemes utilize the communication infrastructure and advanced signal processing techniques that are employed for islanding detection. Remote schemes have negligible NDZ and high reliability in comparison with local IdMs [24]. Owing to high cost, complexity, and implementation problems, such schemes are not preferred. Similarly, the conventional passive schemes do not perform well in advanced IPDNs consisting of inverter-based DGs with different system configurations. Therefore, the researchers and engineers are finding alternatives to tackle this challenge. In this framework, many reports on modified passive IdMs have been presented recently. The modifications are performed by applying advanced signal processing techniques and intelligent classifiers to conventional passive schemes for having fast, reliable, and accurate detection methods. A schematic representation of various IdMs is shown in Figure 1, which are being studied and investigated for years. With the advancement in grid integration technologies and application of modern signal processing and intelligent tools, the performance of such methods is improved significantly. In the following section, various IdMs are discussed briefly.

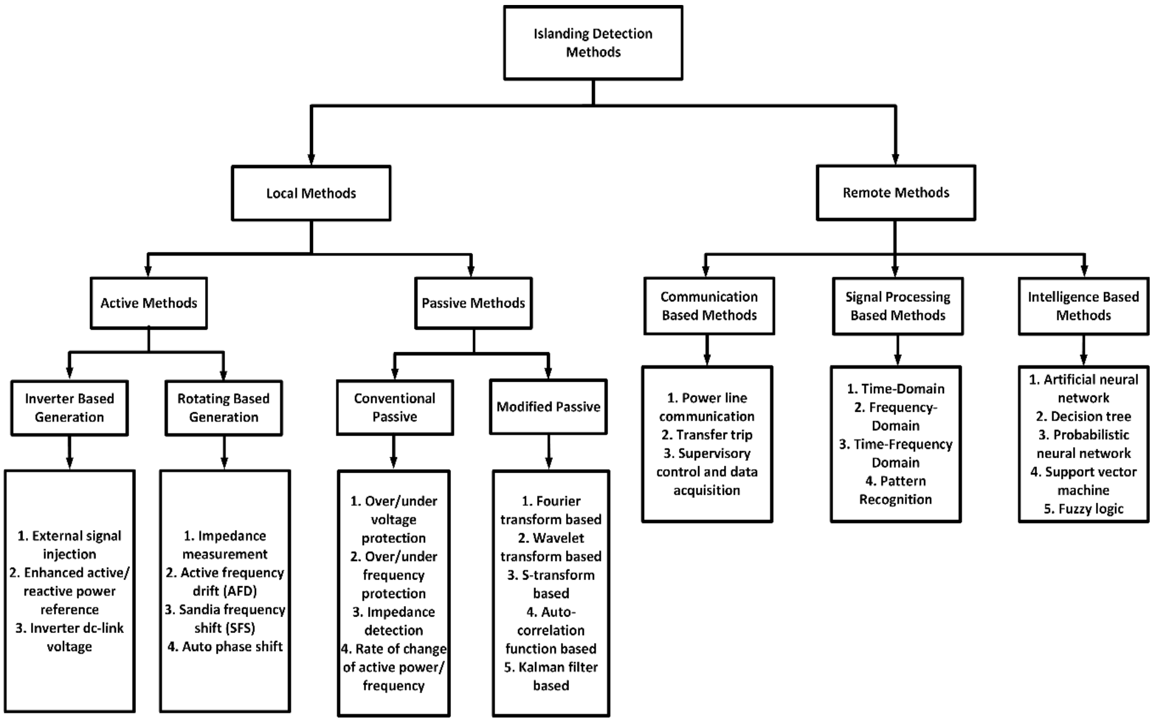

Figure 1. Classification of Various IdMs.

3.1. Active IdMs

Active techniques are based on injecting a small perturbing signal into the DG output. The external signal injection brings significant variations in the system parameters under the islanding condition, and triggers the relays to operate. Active techniques may cause power quality problems and harmonic disturbance due to external signal injection, and therefore, the system performance can be degraded [25]. Impedance measurement (IM), active frequency drift (AFD), Sandia frequency shift (SFS), Sandia voltage shift (SVS), and sliding mode frequency shift (SMFS) are some of the examples of active IdMs [26]. Active IdMs are mostly developed for inverter-based DG systems [27]. Given that synchronous DGs may deviate the frequency control or reactive power output by inducing a destabilization error upon islanding, active IdMs use intelligent relays and more efficient algorithms [28]. A brief description of active detection techniques is given below.

3.1.1. IM Method

The IM method is based on the variation in the high-frequency impedance of the estimated data gathered from voltage and current measurements [29]. The high-frequency impedance signal becomes more significant during the islanding condition. The IdMs based on IM are mostly used for the power systems comprising synchronous DG units. The IM method possesses a small NDZ for the systems comprising single inverter-based DG units and the local loads having a larger impedance than the main utility grid impedance [30]. The injection of the high-frequency signal in IM methods produces voltage or current harmonics, which affect the performance of such methods [31]. Moreover, the threshold selection in IM-based IdMs is also a difficult task, which can be affected due to the strength of the injected signal.

3.1.2. AFD Method

The AFD method utilizes a slightly distorted inverter current waveform that is injected into the point of common coupling (PCC) or DG terminals [32]. During the grid-connected operation, the voltage and frequency waveforms do not change at DG terminals owing to the grid stability, while keeping the frequency of the inverter current unchanged. However, when the main grid is disconnected, a zero crossing of the voltage occurs due to the perturbing signal injection, which gives rise to the phase error (between the output voltage and inverter current). Thus, a frequency drift of the inverter's output current is observed, which eliminates the phase error [33]. This frequency drift originates another zero crossing until the voltage frequency exceeds the pre-defined threshold limit, thereby detecting the islanding condition. The performance characterization of the AFD method has been discussed in [34], which describes the relation between inverter current distortion and load resonant frequency as follows:

$$\arg\left\{R^{-1} + (j\omega L)^{-1} + j\omega C\right\}^{-1} = 0.5\omega t_z = 0.5\pi \cdot cf \tag{1}$$

where ω is the frequency of inverter voltage, cf is the chopping fraction, and t_z is the zero or dead time of AFD.

3.1.3. SFS Method

The SFS [35] method is basically an extension of the AFD method where a positive feedback is applied to the inverter voltage frequency with a connection to the utility grid. When the main grid is disconnected, the change in frequency introduces an inverter phase angle error, which continues until the frequency exceeds a pre-defined threshold limit [36]. For the SFS method, an appropriate selection of parameters such as chopping frequency cf_o and accelerating gain k is an essential task that significantly affects the overall detection performance. The inverter phase angle and SFS parameters [37] are expressed as follows:

$$\varphi_{Inv} = \pi(cf_o + k(f - f_n)) \tag{2}$$

where φ_{Inv} is the inverter phase angle, f is the islanding frequency, f_n is the nominal frequency, and cf_o and k are the SFS parameters.

3.1.4. SMFS Method

The SMFS method uses the phase angle of the inverter output current, which is controlled as a function of terminal voltage frequency [38]. The SMFS method utilizes positive feedback to change the phase voltage at DG terminals by monitoring the frequency deviations, thus detecting the islanding condition. The change in the phase angle of the inverter output current is always relative to the grid output voltage; thus, the frequency of the grid voltage deviates from its nominal value upon the main grid disconnection. The phase angle perturbation sometimes leads to the measurement or quantization error, which is addressed through the introduction of the improved SMFS method [39].

3.1.5. SVS Method

In the SVS method [40], a positive feedback is applied to the voltage amplitude at the output terminals of the DG unit or PCC. In the grid-connected mode, there is a negligible effect on the power system; however, when the grid is disconnected, a significant reduction at the PCC voltage arises. The anti-islanding protection relays detect the reduction and send a tripping signal to the DG control to cease the operation [41]. The SVS method is known to be the most efficient IdM among other feedback-based detection methods. By combining the merits of the SVS and SMS methods, a more efficient IdM can be developed, which might not affect the power quality and perform well.

3.2. Passive IdMs

In passive IdMs, the system parameters including voltage, current, impedance, power, or frequency are monitored at the PCC or DG terminals. These parameters show significant variations when the main grid is disconnected from the IPDN or microgrid. The protection relays thus sense these variations and operate to trip the main breaker switch. The conventional passive schemes include over/under voltage protection (O/UVP) or over/under frequency protection (O/UFP), the rate of change of frequency/power (ROCOF/P), and phase jump detection (PJD) methods [42]. The passive approaches do not affect the power quality or grid operations. The drawbacks of passive IdMs include larger NDZ and lesser detection speed. A brief description of the passive IdMs is given below.

3.2.1. O/UVP or O/UFP Method

In the O/UVP or O/UFP method, the conventional protection relays are installed on a distribution feeder to determine the abnormal conditions during various modes of microgrid operation [43]. These methods are based on the selective threshold values of voltage and frequency relays at common DG terminals. The relays start the operation when the voltage and frequency values cross the set threshold limits, thus disconnecting the DGs from the main utility network [44]. Usually, the utility grid operations depend upon the changes in the active and reactive powers (ΔP and ΔQ) before a disconnection from DG sources may occur. At the non-zero ΔP, a change in the amplitude appears at PCC, which the O/UVP relay detects and disconnects the DG. On the other hand, at non-zero ΔQ, a load voltage phase shift appears, which deviates the inverter current frequency. The O/UFP relay detects this change and disconnects the DG. Such a method is simple and cost-effective owing to no additional circuitries or control loops.

3.2.2. ROCOF/P Method

The ROCOF/P [45] method monitors the changes in the frequency or DG output power, which appear during the islanding occurrence. When the supply of the main grid is lost, a sudden power imbalance occurs and deviates the frequency of the power system at the DG terminals. The change in the frequency by considering df/dt is measured for a short period of time to compare it with the set threshold limit [46]. If the deviation exceeds the pre-specified threshold limit, islanding is detected and the relay sends the tripping signal to the breaker. Usually, the tripping time for the frequency relays used in ROCOF-based IdMs should not exceed four to six cycles.

Similarly, when the main utility grid is disconnected, a sudden load change is observed in the output power of the DG system. The ROCOP method monitors the change dP/dt measured at DG terminals and integrates for a specific time interval. Upon exceeding the signal strength, the trip setting is altered and the islanding condition is detected. Compared to the O/UVP and O/UFP methods [47], the ROCOP-based IdM is fast and not affected by the small power mismatches between the DG and local loads.

3.2.3. PJD Method

In the PJD method [48], a phase difference between the voltage and current at DG terminals is monitored for a sudden phase jump. During the islanding condition, a change occurs in the phase angle, which is compared with the preset threshold value. The PJD method works well with multiple inverters by using a phase-locked loop and does not affect the power quality. The method fails to detect the islanding condition when the DG power and local load are closely matched. Therefore, the PJD method suffers from large NDZ. Moreover, PJD may create maloperation due to the power system switching events. The NDZ of the PJD method is derived using the following expression as:

$$tan^{-1}\left(\frac{(\Delta Q/P)}{1+(\Delta P/P)}\right) \leq \vartheta_{threshold} \quad (3)$$

where $\vartheta_{threshold}$ denotes the phase-jump threshold. The circuit reactive elements may affect the accuracy of the PJD method, therefore, it is not suitable for industrial applications.

3.3. Remote IdMs

The remote techniques are based on the communication links between the utility grid and DG sources. These methods perform efficiently and have negligible NDZ. An NDZ is also defined as a range of operational power region that is not protected by conventional protection devices [49]. Therefore, conventional IdMs usually have a large NDZ. Although remote techniques have better reliability than local IdMs, they are uneconomical [50]. The higher cost, high computational burden, and complexity in operations are the main drawbacks of communication-based IdMs. Figure 2 shows a schematic of the remote islanding detection scenario, where the main grid and DG unit share the information using a communication channel. Islanding detection is mainly based on the information collected from the applied media and sent to the tripping switch. The common examples of remote IdMs include the power line communication (PLC), supervisory control and data acquisition (SCADA), and transfer trip methods.

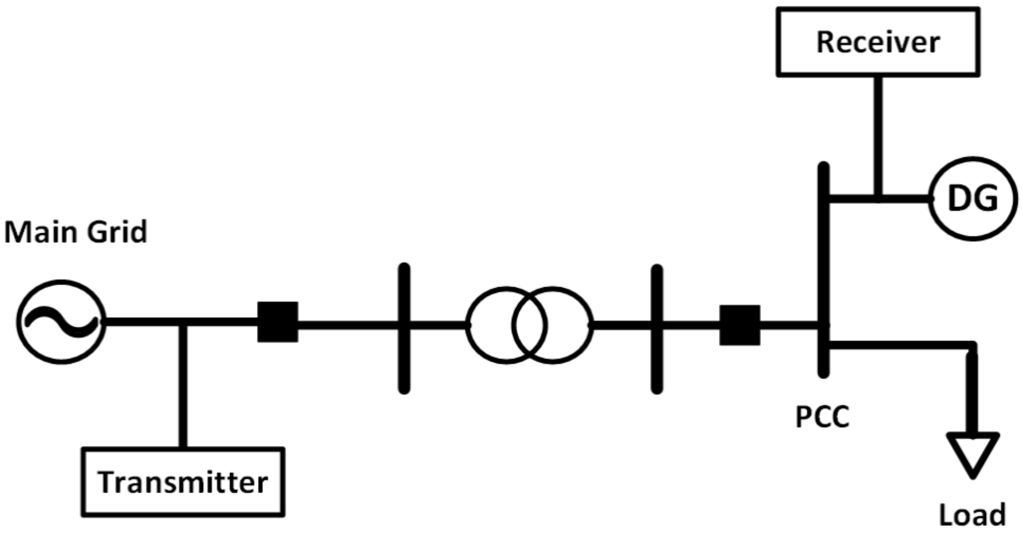

Figure 2. Remote islanding detection scenario.

3.3.1. PLC Method

The PLC method detects the islanding condition using the communication signals through the power lines. In this method, a transmitter device sends a continuous low-voltage signal to the microgrid or DG side using power line carriers that are equipped with a receiver device. Usually, the sending signal is designed with four consecutive cycles, and the islanding condition is detected if the signal disappears for two to three cycles [51]. Such method is suitable for large-scale integrated power networks due to the increasing costs and other complexities.

3.3.2. SCADA Method

SCADA-based IdM is used to continuously monitor the breakers and other switching and control circuits. In a SCADA system, electrical parameters such as voltage, current, frequency, or power are controlled by sensitive devices to detect any loss in the system. When the islanding phenomenon occurs, the grid parameters are suddenly altered, and thus, the audible alarms start ringing and the relays operate to disconnect the DG sources. Moreover, the implementation of SCADA systems guarantees a synchronized operation of the microgrid and utility grid to avoid any phase difference [52]. In addition, it provides easy restoration after the disappearance of the disturbance.

3.3.3. Transfer Trip Method

In the transfer trip method, a supplementary control of the DG system through the utility grid is achieved [53]. Usually, the transfer trip method is integrated with the SCADA system to monitor the operating switches while providing an efficient coordination between the microgrid and the main grid. Such methods have negligible NDZ and provide fast islanding detection. However, this method exhibits hardware limitations, high cost, and risk of communication failure.

3.4. Modified Passive IdMs

The modified passive IdMs utilize signal processing techniques to improve the detection performance, decrease detection time, and reduce NDZ. The application of well-known time-domain, frequency-domain, and time-frequency-domain signal processing tools such as Fourier transform (FT), wavelet transform (WT), S-Transform (ST), time-time transform (TTT), autocorrelation function (ACF), and Kalman filter (KF) have helped the researchers improve the existing islanding detection schemes and develop new methods. These tools help to analyse and extract the important features of a measured signal in order to perform efficient power system operations. Some of the signal processing techniques being utilized for islanding detection are described below.

3.4.1. FT-Based Method

FT is a frequency-domain analysis tool used to extract the features of a signal at the specified frequencies. FT is not capable of considering time-domain analysis, and therefore, short-time Fourier transform (STFT) is considered to evolve numerous frames of the signal in the moving window. Other dominating techniques consider the discrete Fourier transform (DFT) and fast Fourier transform (FFT), which transform the finite length of the discrete-time sequence into a discrete-frequency sequence. Researchers have utilized such tools to develop efficient and fast IdMs [53]. Besides the advantages, there is a certain limitation in FFT-based schemes, including reduced spectral estimation and low-frequency resolution [54].

3.4.2. WT-Based Method

Wavelet transformation is a strong candidate for extracting important features from a distorted voltage, current, or frequency signal. Methods based on WT are associated with STFT and the multi-resolution techniques [55]. In WT-based IdMs, the wavelet coefficients of the measured signal are compared with the pre-defined threshold value. If these coefficients attain a larger value than the pre-defined threshold value, the islanding condition will be detected. The impacts of mother wavelet selection, threshold settings, and different sampling frequencies are the limitations of such methods. Moreover, WT can only analyse the low-frequency band, and therefore, the wavelet packet transform (WPT) is applied to analyse the high-frequency components using the d-q axis of three-phase apparent power [56]. The WPT method is mostly related to the discrete wavelet transform (DWT), except for the fact that WPT gives equal resolution to low- and high-frequency signals. WPT can extract significant features from a measured voltage or current signal using approximation and detail decomposition.

3.4.3. ST-Based Method

ST is an extension of the WT concept. It converts a time-domain function into a two-dimensional frequency-domain function. Like other time-domain methods, the ST method is also utilized to extract important features from a measured signal at PCC, thereby detecting the islanding condition. Initially, ST processes the measured voltage or current signals at DG terminals and generates the S-matrix and the equivalent time-frequency contours. Then, the spectral energy content of these contours is calculated as containing the information of frequency and magnitude deviations for islanding detection [57]. To process a signal, the ST method requires more computational memory than the other similar techniques. Moreover, the processing time of such methods is large.

3.4.4. TTT Based Method

The TTT method analyses and transforms a one-dimensional time-domain signal into a two-dimensional time-domain signal by giving time-time distribution on a particular window [53]. In the TTT method, the low-frequency components are concentrated at different positions, whereas the high-frequency components are concentrated around the localization point having more energy concentration. One of the TTT features is its time-local view utility through the scaled window, which makes it a suitable method for change detection in the signal and systems. TTT-based IdMs show good performance in a noisy environment [58].

3.4.5. ACF Based Method

ACF is a mathematical tool used to extract the hidden information from a measured power or energy signal. While considering the finite-duration sequences, ACF is expressed using the finite-summation limits. A modified passive IdM based on the ACF of the modal current envelop was utilized for islanding detection in [42]. The method uses the calculated envelopes derived by the Hilbert transform approach to extract transient features, for which the variance of samples provides the criterion for islanding detection.

3.4.6. KF Based Methods

KF is a well-known time-frequency-based harmonic analysis tool used in power systems to extract and filter harmonic features from the measured voltage or current signals. In [59], an IdM based on KF is proposed, which utilizes voltage harmonics and selected harmonic distortion (SHD) for islanding detection. In the proposed method, a two-step criterion for implementation is achieved using the residual signal and SHD. The islanding condition is classified using the residual signal, whereas the SHD criterion is used for the detection purpose in a timely manner.

3.5. Intelligent IdMs

Intelligent IdMs are similar to communication- or signal processing-based methods, except that they do not require threshold selection. Various intelligent classifiers and data mining techniques are being utilized for islanding detection purposes. The commonly used intelligent IdMs associated with signal processing techniques include the artificial neural network (ANN), decision tree (DT), probabilistic neural network (PNN), support vector machine (SVM), or fuzzy logic (FL). Such techniques are capable enough to sort out the multi-objective problems which the conventional approaches cannot handle. Figure 3 shows a schematic of intelligent IdMs. First, the input signal in the form of voltage or current measured at the PCC is fed to the system for data training and feature extractions using a training algorithm. This process is performed offline in order to save time and avoid computational burden. The online process is performed using an intelligent classifier model for making the final decision. In general, the intelligent IdMs suffer from the large computational burden. A brief discussion of intelligent IdMs is given below.

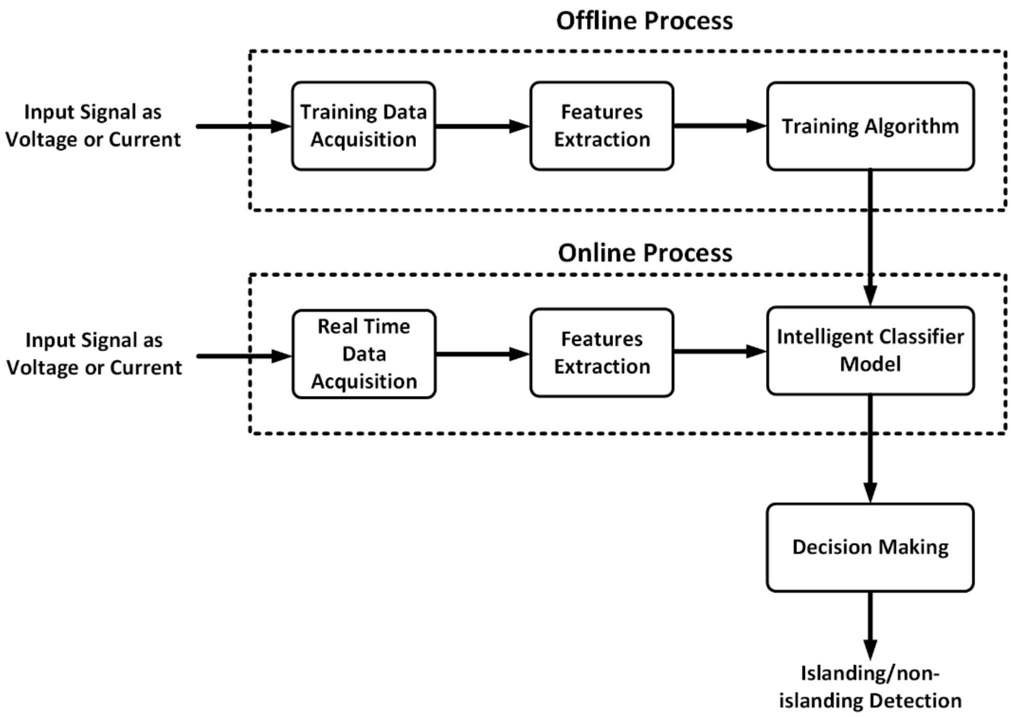

Figure 3. Schematic of intelligent IdMs.

3.5.1. ANN-Based Method

The ANN-based approaches extract important features from the measuring data, which are used for identifying the variations in power system parameters. ANN can be described as a computational model of a biological procedure, which tries to instrument a mathematical model using the biological brain of the neural network [60]. All useful information and data memory are in the neural network brain. ANN-based IdMs detect the islanding condition by providing a high-accuracy and suitable operation for the systems using multi-inverters [61]. ANN-based schemes perform the islanding detection efficiently, but a large processing time and feature selection with multiple DG configurations still need to be addressed.

3.5.2. DT-Based Method

DT is another classification technique that is utilized for islanding detection. In various signal processing or intelligent IdMs, the DT classifiers with a combination of WPT or DWT are used [62]. Usually, the voltage or current signals measured at DG terminals are fed to WPT or DWT for feature extractions. The extracted features are then further processed using a DT classifier to detect the islanding condition. A DT-based IdM using the transient-state signals is presented in [63]. Based on the assessment results on the CIGRE distribution system, the method has achieved an accuracy of 98%.

3.5.3. PNN-Based Method

PNN is a classification technique that can compute the non-linear decision boundaries based on a Bayesian classifier. In general, PNN is applied in traditional pattern recognition schemes using the artificial neural hardware. PNN contains the following four layers: the input layer, pattern layer, summation layer, and output layer [64]. These layers perform their functions for feature classifications and do not need any learning technique. Due to the attractive merits of PNN-based methods, they have proven to be a reliable option for islanding detection [65].

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3.5.4. SVM-Based Method

SVM is a powerful classification tool used for signal and system analysis by constructing a decision boundary to split the data needed for training [66]. The SVM classifier, in association with autoregressive modelling, is used to extract the signature features from the measured PCC voltage or current signals [67]. The SVM-based IdMs provide high accuracy and fast detection speed. However, due to the large computational burden regarding the data training and algorithm complexity, SVM-based IdMs are considered impractical for real system implementations.

3.5.5. FL-Based Method

The FL techniques are applied as a fuzzy-rule-based classifier method for islanding detection. FL was first introduced using DT transformation, where the combination of fuzzy membership functions and the rule-based formulations were used to improve the fuzzy systems [68]. Such methods show an efficient performance when applied in islanding detection algorithms. However, the fuzzy classifiers have limitations for being highly abstract due to several maximum and minimum class combinations. Moreover, FL-based approaches are sensitive to noisy data due to repeated generation of rules of membership functions and classifications [69]. Table 1 characterizes the various IdMs in terms of their merits, demerits, and other performance capabilities

Table 1. Characterization of IdMs.

Classification of IdMs			Principle of Operation	Merits	Demerits	Computation Burden	Detection Speed	NDZ
Local	Active	Inverter-based	Injecting perturbation or external frequency signal	Accurate & easy to implement	Impact of complex control loop modifications & switching transients	Medium	Medium	Small
		Rotating based						
	Passive	Conventional	Monitoring change in system parameters at PCC	Simple & easy to implement	Poor reliability	Low	Low	Large
		Modified		Accurate, Simple and fast	Hard to select a threshold value		High	Small
Remote		Communication-based	Communication b/w DG and Utility	Accurate, Efficient, fast, & Reliable	Complex, sensitive, expensive & mostly used for large-scale power systems	High	High	Very Small
		Signal processing based	Feature extraction			Medium		
		Intelligence based	Pattern recognition & data training			High		

4. Islanding Detection Standards

Several well-known international organizations such as IEEE and IEC have defined certain standards for interconnection, operation, and control of DG systems with the main utility grid. Such standards offer requirements relevant to the performance, testing, safety considerations, and maintenance of the integrated power system networks. UL-1741 and IEEE 1547 standards for anti-islanding protection are used to assess the performance evaluation of IdMs [70]. The main clauses of these standards are listed below:

- Monitoring the magnitude and direction of the power-flow
- A DG unit must be disconnected within a time limit of 2 s if the main utility has gone out of service
- Observe the characteristics and functionality of DG units
- Proper control of voltage, frequency, and power quality
- The contributing and non-contributing DG need to be identified

In parallel with these considerations, the transformer grounding configurations need to be maintained under all operating conditions. These standards help researchers to design efficient IdMs by considering all above factors. Table 2 shows various standards for islanding detection, which consider load quality factor, detection time, and voltage-frequency operating ranges.

Table 2. Standards for Islanding Detection.

Parameters	IEEE Std. 1547-2003	IEEE Std. 929-2000	IEC 62116	Korean Standard
Quality Factor	1	2.5	1	1
Detection Time	t < 2 s	t < 2 s	t < 2 s	t < 0.5 s
Allowed Frequency Range (nominal frequency f_o)	59.3 Hz $\leq f \leq$ 60.5 Hz	59.3 Hz $\leq f \leq$ 60.5 Hz	(f_o-1.5 Hz $\leq f$ and $f \leq$ (f_o + 1.5 Hz)	59.3 Hz $\leq f \leq$ 60.5 Hz
Allowed Voltage Range (nominal voltage V_o)	0.88 $\leq V \leq$ 1.10	0.88 $\leq V \leq$ 1.10	0.85 $\leq V \leq$ 1.15	0.88 $\leq V \leq$1.10

5. Performance Analysis

The performance of the IdMs mainly depends on a timely and accurate operation of the corresponding method. There are three main performance indices that characterize the operational capability of an IdM: NDZ, parallel RLC load, and load quality factor. The usefulness of IdMs is confirmed by a successful operation under these extreme circumstances. If a method successfully detects the islanding condition under such circumstances, the superiority of the method is highlighted, and is satisfied by the international standards.

5.1. NDZ

In islanding detection, NDZ is defined as a region that is not easily detected by conventional protection relays. Usually, an NDZ is evaluated on the basis of an active and reactive power mismatch range in which the voltage and frequency relays cannot detect the islanding condition in a timely manner. If the power mismatches ΔP and ΔQ at PCC are small enough, the frequency and voltage fluctuations after the islanding occurrence will not vary sufficiently to detect the islanding condition [71]. The relation between the thresholds of power mismatch and voltage/frequency limits can be derived using the following equations.

$$\left(\frac{V}{V_{max}}\right)^2 - 1 \leq \frac{\Delta P}{P} \leq \left(\frac{V}{V_{min}}\right)^2 - 1 \tag{4}$$

$$Q_f\left(1 - \left(\frac{f}{f_{min}}\right)^2\right) \leq \frac{\Delta Q}{P} \leq Q_f\left(1 - \left(\frac{f}{f_{max}}\right)^2\right) \tag{5}$$

where V_{max}, V_{min}, f_{max}, and f_{min} are the maximum and minimum voltage/frequency threshold limits of the relays in the DG system; ΔP and ΔQ represent the power mismatches prior to the main grid disconnection; and Q_f is the load quality factor usually considered to define parallel RLC load. Using (4) and (5), the NDZ boundary limits can be defined and one can discriminate the area of critical and non-critical operating conditions.

5.2. Parallel RLC Loads

Most of the loads in power systems are inductive in nature, whereas inverter-based DG units mostly operate at unity power factor to produce maximum kilowatt-hours. Such a condition, in combination with a parallel RLC load, is considered as a worst-case scenario to detect the islanding. Similarly, when there is a perfect match between the connected load and DG power, islanding detection becomes more difficult. Therefore, test systems comprising inverter-based DGs and parallel RLC loads are used as a benchmark to evaluate the capability of IdMs. The RLC load consists of linear components where the resonant frequency remains the same as the grid-line frequency [71]. A generic system for islanding detection under UL-1741 test is shown in Figure 4, where the system contains a parallel RLC load, a DG unit, and a utility grid. For a parallel RLC circuit, the relation between the PCC voltage and frequency is given as follows [72]:

$$P_{load} = \frac{3V_{PCC}^2}{R} \tag{6}$$

$$Q_{load} = 3V_{PCC}^2\left(\frac{1}{\omega L} - \omega C\right) \tag{7}$$

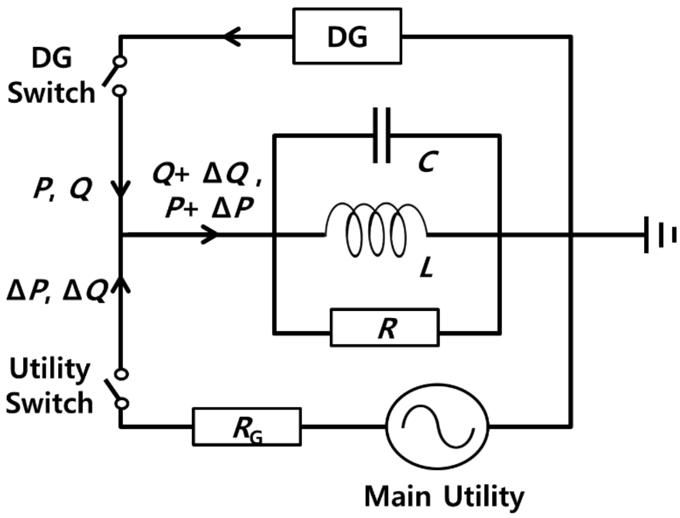

Figure 4. A generic system of islanding detection.

From (6) and (7), V_{PCC} is clearly dependent on the active power of the islanded system. Similarly, a deviation in the frequency at the PCC for the DG system operating at unity power factor will be observed if the load on the islanded system absorbs the reactive power. The load inside the islanded system possesses a high-quality factor Q_f due to the varying characteristics of resistances, inductances, and capacitances. Therefore, the parallel RLC loads with a high Q_f often create technical challenges during the islanding detection process.

5.3. Load Quality Factor

The load quality factor is an important parameter used to determine the reliability and robustness of any IdM [73]. The load quality factor affects the size of NDZ and detection accuracy, and therefore, the performance analysis of the IdMs significantly depends on the value of the load quality factor. Assuming that $Q_f = 2$, there is twice as much energy stored in the inductor or capacitor of the load as is being dissipated in the resistor. The loads near the resonance having a high Q_f may cause difficulty in islanding detection. Mathematically, the quality factor is defined as follows:

$$Q_f = R\sqrt{\frac{C}{L}} = 2 \tag{8}$$

where R, L, and C are the effective load resistance, inductance, and capacitance, respectively, and Q_f is the quality factor. From the above discussion, the size of NDZ significantly depends on the value of Q_f but is relative to the active and reactive power mismatches.

6. Comparison of Various IdMs

After a comprehensive review and in-depth analysis, a comparison of various IdMs considering different capability parameters is presented in Table 3.

Table 3. Comparison of Various IdMs [5,11,27,35,50,58,59,64,73].

Type		Based On	Merits	Demerits	Computation Burden	Speed
Conventional Passive		OVP/UVP	1. Simple 2. Economical 3. Easy to implement 4. Good for large power mismatch	1. Low reliability 2. Creates maloperation 3. Hard to select the threshold 4. Low NDZ	Very Low	Within 2 s
		OFP/UFP				
		ROCOP				
Modified Passive	Signal Processing-based	WT	1. Provides multiple resolution 2. Variable window size 3. Suitable candidate to analyze the signal signatures in different perspectives	1. Sensitive to noisy signals 2. Extract only the low-frequency band 3. Computationally complex	Medium	Around 1 s
		STFT	1. Provides good resolution 2. Frame-based processing	1. Fixed window size 2. Individual frequency components are not localized in the window	Low	
		KF	1. Sample-wise response 2. Variable window size/Adaptive 3. Robust against the noisy environment	1. Deriving KF formulation for complex system is a challenge. 2. Limited to specified harmonics estimation		
	Intelligence-based	ANN	1. Good accuracy 2. Used for multiple inverter-based DG Units 3. No threshold selection required	1. Highly abstract 2. Require large data for training	High	Less than 1 s
		SVM				

The operating capability of any IdM significantly depends on these indices. For a fair comparison, the implementation process and limitations of various methods must be known, and therefore, each scheme is critically analysed by referring to reliable and well-known studies. While comparing the IdMs, four important parameters are considered, which include the accuracy, reliability, cost, and side-effects. The accuracy is quantified as low (70% to 80%), medium (80% to 90%, and high (90% to 100%). Similarly, the reliability of the methods is tabulated on the basis of their performances achieved as less or more reliable to various operating scenarios. Moreover, the cost of the methods is assessed on the basis of the required system equipment and run-on components. Finally, the side-effects of IdMs are highlighted by considering their operating principles, computational efficiencies, and capabilities of the utilized approaches.

7. Recommendations and Future Trends

Based on a comprehensive review analysis and known facts, clearly, each IdM has certain advantages and disadvantages. The active methods provide a fast detection speed and small NDZ, but their impact on power quality may deteriorate the performance of the power systems. Passive methods are simple and can detect the islanding condition using conventional protection methodologies. However, these methods may fail to detect the islanding condition when the DG and load power are balanced, therefore suffering from large NDZ. Remote methods have fast detection speed, high reliability, and the ability to perform well with multiple system configurations. However, the implementation cost, computational efficiency, and malfunctioning due to the failure of communication links are the main limitations associated with remote IdMs.

The modified passive IdMs employ time-domain and frequency-domain-based signal processing techniques to increase the detection speed and reduce the NDZ. Moreover, such methods are becoming more reliable and efficient due to the application of signal processing, pattern recognition, and artificial intelligence tools. The intelligent methods rely on different time-frequency-based techniques that extract the data from DG terminals and identify the required signatures for islanding detection. Due to the presence of various training and testing procedures, intelligent methods suffer from a large computational burden, which makes them less favourable in comparison with other modified passive IdMs.

Therefore, based on the above discussions, it can be observed that the modified passive methods are preferred on the basis of simplicity, accuracy, cost, and real-time industrial applications. Moreover, such methods have low computational burden in comparison with remote schemes, thereby appearing as a flexible approach for islanding detection. These methods can also withstand the heterogeneous IPDN, multiple DG-based microgrids, and RLC loads defined by UL 1741 and IEEE 1547 islanding detection standards. The referred work demonstrates that the modified passive IdMs stand robust and efficient against all operating conditions. In the future, hybrid IdMs will likely be a more convenient option, which will surely improve the quality and percentage accuracy of the existing IdMs. Moreover, hybrid techniques may emerge as the best choice for islanding detection in terms of superior efficiency, negligible NDZ, and improved reliability by combining the advantages of active and passive schemes

8. Conclusions

This paper presents a comprehensive review of various IdMs. A broad classification of IdMs, types of power islands, and the issues with unintentional islanding are analysed. Several methods are studied and a comparison is provided on the basis of important capability parameters such as reliability, speed, and computational efficiency. Moreover, the performance indices including NDZ determination, parallel RLC load, and effect of load quality factor are discussed in light of standard islanding detection regulations. The literature demonstrates that the modified passive IdMs are being researched at an accelerating pace and recommended for industrial applications. Hence, the application of time-domain, frequency-domain, and time-frequency-domain signal processing techniques in conventional passive IdMs have reduced the detection time, improved the overall performance, and minimized the implementation cost. Moreover, these IdMs have shown good response time, high accuracy, low computational burden, and high reliability in comparison with other similar methods. Thus, the modified passive IdMs can be considered as a suitable option and optimal solution for DG-based power system network operations in recent times.

This work is a part of an ongoing PhD research. More useful investigations concerning the development of new islanding detection schemes for the integrated electrical power distribution networks are in progress. The development of new schemes will not only provide effective islanding detection options for the integrated networks but will also be more helpful for the academic research and industry applications.

Author Contributions: M.-S.K. and R.H. carried out the main research tasks and wrote the manuscript under the supervision of C.-H.K. R.H. provided the technical support and verified the review contents. G.-J.C., C.-Y.W. and J.-S.C. contributed in preliminary draft preparation and reviewed the paper. C.-H.K. provided the necessary guidelines and managed the research project.

Conflicts of Interest: The authors declare no conflict of interest.

Nomenclature

AC	Alternating current
ACF	Autocorrelation function
AFD	Active frequency drift
ANN	Artificial neural network
CIGRE	International council for large electric systems
DC	Direct current
DG	Distributed Generation
DFT	Discrete Fourier transform
DT	Decision tree
DWT	Discrete Wavelet transform
FFT	Fast Fourier transform
FL	Fuzzy logic
FT	Fourier transform
IdM	Islanding detection method
IEC	International Electrotechnical Commission
IM	Impedance measurement
IPDN	Integrated power distribution network
KF	Kalman filter
NDZ	Non-detection zone
O/UVP	Over/Under voltage protection
O/UFP	Over/Under frequency protection
PCC	Point of common coupling
PJD	Phase jump detection
PLC	Power line communication
PLL	Phase-locked loop
PNN	Probabilistic neural network
RLC	Resistive, inductive, and capacitive
ROCOF	Rate of change of frequency
ROCOP	Rate of change of power
SCADA	Supervisory control and data acquisition
SHD	Selected harmonic distortion
SMFS	Sliding mode frequency shift
ST	S-transform
STFT	Short time Fourier transform
SVM	Support vector machine
SVS	Sandia voltage shift
TTT	Time-time transform
WPT	Wavelet packet transform
WT	Wavelet transform

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