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Comparative Study and Recent Developments of Islanding Detection Methods for Microgrids and DGs

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***Abstract*— The integration of distributed generation (DG) into the distribution networks provides many technological benefits, as improving system security, raising reliability, providing clean source of electricity and reduction in fossil fuel consumption. However the large integration of DGs leads to few concerns like intermittent nature of renewable DGs, complicated protection schemes, islanding of the DGs etc. In the islanded operation, the microgrid/DG keeps power injection to the network. Therefore, islanding detection is an essential aspect of DG systems that ensures safety and reliability of the overall distribution systems. This paper provides a review of various islanding detection methods (IDMs), including local, remote and other approaches. Various detection methods in each section are discussed, based on the performance evaluation of important indices such as non-detection zone (NDZ), detection time (DT), error detection (ED) ratio, power quality (PQ) and efficacy in single or multiple inverter systems. The review aims to provide a thorough understanding of the existing IDMs enabling the development of more efficient and reliable methods.**

***Index Terms*— distributed generation (DG), microgrid (MG), islanding detection method (IDM), point of common coupling (PCC).**

I. INTRODUCTION

The renewable energy contribution in electricity forecasted to raise from 21% in 2024 to 27%, by 2027 in India and globally its 38% by 2027. The distributed renewable energy resources like biomass, wind turbine, photovoltaic generator, battery etc. are connected to the main grid through power electronic interface. The integration of DG into the main grid is advantageous because of the increased productivity of the system, improved quality of power, reduced power losses and gases emission. Nonetheless, this could lead to a set of operational issues associated with system stability and reliability including reverse power flow and islanding issues [1]. There is a need of advanced control and optimization for solving the risks and hazards caused by this expansion. Therefore, to guarantee system and human safety, an effective islanding detection mechanism is essential. When a DG keeps powering nearby loads after the main grid has been cut off or has malfunctioned, this is known as islanding. Safety risks, equipment damage, power quality problems, grid instability, and protection system malfunctions can all result from this condition [2].

DG's safety depends on IDMs. A number of variables, including the particular application, grid properties, and desired performance, influence the choice of an appropriate approach. IDMs can be broadly divided into three categories: local, remote and other emerging methods. Passive, active, and hybrid approaches are classified as local methods that use the DG to measure system parameters.

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To identify islanding, remote techniques use communication channels between the main grid and the DG. Emerging approaches include signal processing-based strategies that concentrate on feature extraction, as well as computational intelligence-based strategies relies on pattern recognition and data training. These methods have a number of drawbacks even though they are frequently successful in identifying islanding. Detecting islanding within the Non-Detection Zone (NDZ), problems with power quality (PQ) and system stability, false detection in systems with multiple DGs, the requirement for extra circuitry or equipment, and high implementation costs are typical problems. More IDM research and development is required to overcome these constraints. It has been suggested that hybrid renewable energy microgrid systems use machine learning algorithms for predictive maintenance, which focuses on the early identification of possible problems to maximize operational efficiency and minimize downtime. The suggested models forecast the remaining useful life (RUL) of crucial components by integrating real-time data from solar, wind, and storage components. The findings show notable increases in forecast accuracy, providing a solid means of boosting the dependability and durability of microgrids powered by renewable energy [3]. This paper provides an overview of IDMs in DG grid-connected systems. Each IDM's fundamentals have been discussed with overall conclusion.

II. Islanding Detection Methods (IDM's) Indices And Technical Problems

The IDMs performance is evaluated based on precision of detection, time for detection, and reliability.

A. Non-detection Zone (NDZ)

NDZ is the operating region of the MG where occurrences of islanding cannot be detected by the IDMs due to power closely matching conditions. It quantifies IDM's accuracy and capability, minimum NDZ indicates proficiency of the IDM. It is due to the parameters of IDMs which certainly does not show the deviations to differentiate between islanding and non-islanding conditions.

B. Power Mismatch (PM)

The PCC parameters namely frequency and voltage varies as a function of the power variations w.r.t DG power generation and the load demand. The islanding detection by conventional methods becomes difficult in case of small PM since parameter variation will be minimal where as a large PM makes it easier to detect.

C. Detection Time (DT)

The DT is time taken by IDMs to detect the MG's disconnection from the main grid.

D. Error Detection Ratio(EDR)

There are operating situations when the IDM falsely recognizes the non-islanding events as islanding. EDR therefore is the ratio of number of false recognitions and total number of islanding recognitions.

E. Power Quality (PQ)

In active methods it's claimed that injection of disturbance may reduce the NDZ, however it adds to compromise the PQ of the grid. Thus, PQ is a parameter of significance for the selection of IDMs [4]. Therefore, NDZ, PM, DT, ED ratio and PQ are considered as indices for testing of IDMs.

III. Islanding Detection Methods (IDMS)

IDMs have been mainly classified into local and remote. Local IDMs basically observes the local variable as threshold parameter, and detects the event primarily by comparing. Whereas in remote methods communication infrastructure is in place to acquire number of variables from multiple node points. Fig. 1 shows the categories of IDMs, and these methods are discussed in the following sections.

A. Local IDMs

Local IDMs used to monitor the system parameters such as voltage, frequency, active power, reactive power, impedance, phase angle and harmonic distortion at the DG end to detect islanding and non-islanding condition. Local IDMs are further classified as passive, active and hybrid methods which are described as follows:

- Passive IDMs: These methods monitor the parameters of the system and compares with the pre-set threshold to identify islanding and non-islanding scenario. These are mainly used by power utilities for their simplicity and low cost. Also it causes no PQ degradation and have a fast DT within 2, as suggested by IEEE 1547. However, these passive IDMs have a large NDZ, high ED rate and the threshold setting requires the special consideration. Several passive IDMs are explained below.

Over/under Voltage (OUV) and over/under Frequency (OUF) method compares the V and f at the PCC to the threshold settings, for detecting the islanding. These parameters deviate due to active and reactive PM between DG and load given in (1) and (2) respectively.

$$\Delta P = P_{DG} - P_{LOAD} \qquad (1)$$

$$\Delta Q = Q_{DG} - Q_{LOAD} \qquad (2)$$

P_{DG} and P_{LOAD} are the active power of the DG and of the load respectively, Q_{DG} and Q_{LOAD} are the reactive power of the DG and load respectively.

With an operating condition of $\Delta P \neq 0$, the voltage deviation occurs at the PCC and with $\Delta Q \neq 0$, the system frequency will change during islanding. This method does not affect the PQ but it has a large NDZ, with a DT of 4 ms to 2s. Voltage Unbalance (VU) at the output of the DG will be caused when MG is disconnected from main-grid. The islanding is detected when VU exceeds the threshold settings. The VU at the time instant'‘t’ is given as (3).

$$VU_t = \frac{NS_t}{PS_t} \qquad (3)$$

Where NS_t is the negative sequence voltage amplitude and PS_t is the positive sequence voltage amplitudes [5]. Rate of Change of Frequency (ROCOF) method functions by monitoring df/dt for a few cycles and compares it with the threshold setting. If islanding occurs under PM between the DG and load df/dt exceeds the threshold and islanding is detected. This method has a fast DT of 24 ms and it is highly reliable. But it has a high ED rate for the systems where high load switching and fluctuation is present.Rate of Change of Frequency over Power (ROCOFOP) method works by monitoring df/dP_L for detection, where ‘f’ is the frequency at the PCC and P_L is load power across the DG terminal. This method has a DT of 100 ms, lower ED ratio, smaller NDZ and higher reliability than ROCOF [6].

- Active IDMs: In these methods perturbations are introduced at PCC to system parameters like frequency, voltage, current, etc. and its impact will be observed. It is expected that PCC parameter changes minimal for non-islanding conditions; whereas visible variation results only during islanding. These methods provide a low ED rate and a smaller NDZ. However, they may cause PQ degradation and necessitate the use of additional power electronic devices to produce the disturbances. Several active IDMs are explained below.

Impedance Measurement (IM) is method where in inverter's output current is varied to exhibit an equivalent impedance while islanding happens due to the voltage variations caused by the current perturbation, which are expressed as the ratio *dv/di*. When the calculated impedance surpasses a predetermined threshold, islanding is detected.

This method produces a small NDZ and a DT between 0.77-0.95 seconds in single-DG systems. However, the detection efficiency drops in multi-inverter systems, and it becomes more difficult to determine the impedance as a threshold; because it necessitates precise knowledge of the grid impedance [1], [7].

The Sandia Voltage Shift (SVS) method is relatively simple to implement, but it may slightly degrade PQ and reduce inverter efficiency due to changes in output power. The SVS method introduces a positive feedback mechanism to perturb the voltage amplitude at the PCC, thereby altering the inverter's output current and power. Under grid-connected events, these power variations have minimal impact on the PCC voltage, but under islanding conditions, the same power changes significantly affect the PCC voltage amplitude, which acts as an indicator for the detection. Sandia Frequency Drift (SFD) is also a similar approach [8].

The Slide Mode Frequency Shift (SMFS) method and the SVS method share conceptual similarities. This method involves perturbing the voltage phase at the DG terminal using a positive feedback loop, and then monitoring the frequency variation that results to identify islanding conditions. The DG operates with a zero-phase angle and a steady frequency under non-islanding conditions. However, the DG's frequency and voltage fluctuate during islanding, increasing the phase angle error. When the frequency variation surpasses a predetermined threshold, islanding is identified. In SMFS, the current-voltage phase angle of the inverter is set as in (4).

$$\theta = \theta_m \, sin(\frac{\pi}{2}\frac{f^{k-1} - f_n}{f_m - f_n}) \qquad (4)$$

Here θ_m is the maximum phase angle at f_m, f_n is the rated frequency, and f^{k-1} is the previous cycle frequency. The implementation of the approach is easy; results in smaller NDZ with a DT of 0.4 s. However, it impacts on PQ of the system [5].

- Hybrid IDMs: A sequential operation of passive and active methods is combined in hybrid IDMs. The system is first observed using passive methods to spot any indications of possible islanding followed by an active approach to confirm and precisely detects the islanding. Several hybrid IDMs are explained below.

Voltage Unbalance (VU) and Frequency Set-Point method works monitoring continuously VU at the DG terminal to observe the suspicion and the positive feedback mechanism for precise detection by modifying the frequency set-point of the DG when islanding takes place. The DT of this approach is between 0.15-0.21 seconds [8].

Hybrid Sandia Frequency Shift and $Q{-}f$ method used to reduce the NDZ by adding a $Q{-}f$ droop curve to maintain the optimal gain K_f at a stable value. The authors in [9] proposed a $Q{-}f$ droop curve method that maintains the K_f to a stable value and monitors the change in frequency for detection. During non-islanded operation, the reactive power requirement is managed by the grid; whereas while islanding the DG units which operates at unity power factor, produce no reactive power, this creates a difference in frequency between the actual and the rated system. Therefore, this method monitors the change in frequency for islanding detection and has a DT of 1.4 s.

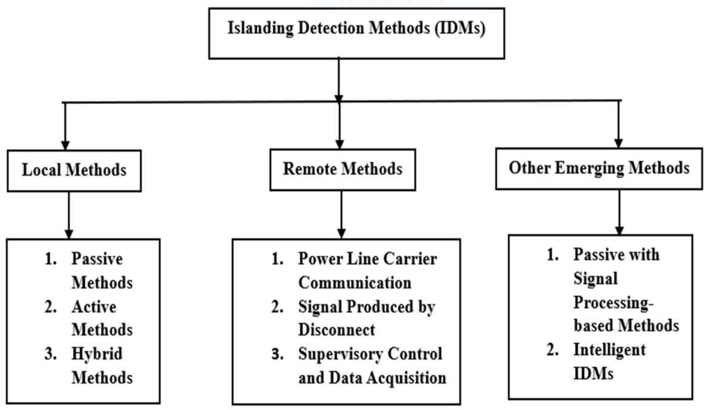

Fig.1 Categories of IDMs

B. Remote IDMs

The remote methods employ advanced signal processing and communication infrastructure and results in negligible NDZ, ED rate can be eliminated, importantly PQ issues doesn't arise in these approaches. However, remote methods are costly to be utilized for small MG, and found suitable for large MG applications. Several remote methods are explained below.

Power Line Carrier Communication (PLCC)/Power Line Singling Scheme (PLSS): PLCC employs receivers and transmitters that are situated at the DG side and the grid side, respectively. Along with the power line, transmitters generate a communication signal; if the transmission is disrupted, islanding is detected. This method can identify islanding if the signal is dropped for three consecutive cycles, and it has a signal period of four consecutive cycles. With a DT of 200 ms, no NDZ, and no effect on PQ, this method is effective for multiple inverter systems as well. However, the cost of the grid-side transmitter makes this approach unfeasible for low power DG systems [5],[8].

Signal Produced by Disconnect (SPD): SPD is similar to PLCC that employs signal transmission between the DG side and the grid. However, rather than using a power line, this technology transmits signals through telephone, microwave and other means. Although there is no NDZ with this approach, setting up the communication line is expensive [8][14].

Supervisory Control and Data Acquisition (SCADA): This system monitors the main grid parameters like voltage, current and frequency, and that can also be used to monitor the condition of circuit breakers and sends it to the MG. The NDZ can be eliminated. But the DT of this method is slow and is expensive to install the separate instrumentation link [8][14].

C. Other Emerging Methods

The local and remote IDMs which are discussed above have their own advantages and limitations. In this concept, the emerging methods have been discussed that is passive with signal processing, and intelligent IDMs that can overcome the drawbacks of local and remote methods such as NDZ, DT, and selecting the threshold to detect islanding, but the data-training process is time-consuming.

Passive with Signal Processing-Based Method: The passive IDMs with signal processing method is discussed that improves detection time, reduces NDZ and improves detection performance. The signal processing tools helps to retrieve and analyse the measured signal to perform the required operation. Several methods are discussed below.

Fourier Transform (FT)-Based method retrieves the attributes of a signal at certain frequencies by using frequency domain. Short time FT, discrete FT and fast FT have been evolved to develop fast and efficient IDMs [10], [11]. However, this method has some drawbacks like low-frequency resolution and reduced spectral estimation. Wavelet Transform (WT)-Based method is used to retrieve the attributes of a distorted signal like current, voltage or frequency. The WT-based is the finest signal processing-based method. This signal compares the measured signal with a pre-set threshold value, and the islanding is detected if the measured values exceed the threshold. Several types of WT like continuous wavelet transform (CWT) and discrete wavelet transform (DWT) are used to retrieve features and classify the islanding events. This method has limitations, such as it can only analyse low frequency band and selection of threshold is challenging [12]. Kalman Filter (KF)-Based method is used, when the measured current or voltage signals are used to retrieve the harmonic attributes by using time-frequency domain. Voltage harmonics and the KF-based selected harmonic distortion (SHD) approach are used for islanding detection. As a prerequisite for islanding detection, the residual signal and SHD are utilized, whereby the residual signal is used for islanding and the SHD is used for timely detection [12].

Intelligent IDMs: Passive IDMs combined with artificial intelligence provides the most effective and economical method for islanding detection. These methods have a high accuracy, reliability, less complex, higher computational efficiency and do not require any threshold selection like other methods. The only drawback of these methods is they suffer from a large computational burden. Few intelligent IDMs are discussed below.

Artificial Neural Network (ANN)-Based method retrieves the important attributes from the measured data to identify deviations in system parameters. The method has high accuracy and performs well with the multi-inverter systems. However, the data processing time is large. Probabilistic Neural Network (PNN)-Based method implements the conventional pattern recognition algorithms using artificial neural circuitry. Its four layers which consists of input, pattern, summation and output, calculates non-linear decision boundaries derived from Bayesian classification approach. These layers do not require learning to accomplish their tasks. IDMs derived from PNN are reliable to detect islanding. Support Vector Machine (SVM)-Based method is used, when the observed voltage or current signals at the PCC are used to retrieve the key attributes to indicate the occurrence of islanding by using SVM classifier and autoregressive modelling. SVM-based IDMs have a high accuracy and a quick DT, but their practical applications are complicated by the algorithm and data training [5],[8].

IV. Modified Islanding Detection Methods

A. Phase Angle of Positive Sequence Voltage (PAOSV)

A passive IDM is proposed using phase angle of positive sequence voltage (PAOSV). The PAOSV was selected based on evaluating 13 different passive indices. The analysis has been done that it has the best sensitivity and has the ability to distinguish between islanding and non-islanding events. This method can detect islanding within 0.10 s even with a zero NDZ [13].

B. Phase Angle Difference of Superimposed Impedance (PADSI)

A passive based IDM is proposed which uses the information of phase angle difference of superimposed impedance evaluated at both DG and PCC ends. To analyse the event the information is transmitted from PCC to DG end for every cycle. The islanding is detected within 2.5 cycles, that is less than 2 s [14].

C. Phasor Measurement Unit (PMU)-Based Method

The two types of methods are tested one is passive and other is hybrid approach with the help of phasor measurement unit (PMU). Passive method uses only one PMU device whereas the hybrid approach uses two PMU devices which is more effective than passive approach. The islanding event can be identified by monitoring the parameters with the help of PMU1 and PMU2. The DT is less than 300 ms [15].

D. Voltage Unbalance (VU) and Reactive Power Change with Positive Feedback

The hybrid method is proposed by using VU (passive approach) and reactive power change with positive feedback (active approach). The reactive power disturbance method with positive feedback is only activated when voltage unbalance method detects there might be an event of islanding. The DT of this method is 0.445 s, which is very much less than 2 s. This method has better performance to detect islanding and eliminates the NDZ [16].

E. Rate of Change of Voltage Unbalance using Wavelet Transform (ROCOVU-WT)

The problem of a large NDZ is addressed by the hybrid approach. This method establishes a threshold value for islanding detection by employing the wavelet transform to analyse the rate of change of the Voltage Unbalance Factor (VUF). This method achieves an average detection time of 0.027961 seconds. With a zero NDZ, it provides dependable and quick performance [17].

F. Reference Current Disturbance

The proposed hybrid IDM detects a possible islanding event when the PCC voltage's absolute deviation surpasses a predetermined threshold. In order to lower the voltage source inverter's active power output, a transient disturbance is added to the d-axis reference current after this detection. This causes a discernible decrease in PCC voltage during islanding, but the voltage fluctuates very little when connected to the grid. When a concurrent drop in PCC voltage and active power output is noted, islanding is verified. The DT is found to be less than 300 milliseconds and results in small NDZ [18].

G. Variational Mode Decomposition (VMD) based method

A passive islanding detection algorithm is proposed based on VMD approach. It says that islanding can be detected when VMD attributes are compared to threshold. This method is reliable and DT is 0.06 s [19].

H. Second Generation Wavelet Transform (SGWT) and Maximum Overlap Discrete Wavelet Transform (MODWT) approach

A new passive IDM is proposed using Second Generation Wavelet Transform (SGWT) and Maximum Overlap Discrete Wavelet Transform (MODWT). The ripple content of voltage signal at the PCC is measured. It is done through by decomposing the signal using SGWT and MODWT approach. This method detects islanding at 0.3 s, even with a zero-PM [20].
Table 1. Shows the comparison of IDMs and modified IDMs based on performance evaluation indices such as NDZ, DT, ED rate and PQ.

TABLE I. COMPARISON OF IDMS

Detection Method	**NDZ**	**DT**	**Impact on PQ**	**ED Rate**
Passive (Local)				
OUV/OUF	Large	4 ms-2 s	No	Low
ROCOF	Small	24 ms	No	High
ROCOFOP	Smaller than ROCOF	100 ms	No	Low
VU	Large	53 ms	No	Low
Active (Local)				
IM	Small	0.77-0.95 s	Degrades	Low
SVS	Smallest	0.5 s	Slightly degrades	Low
SMFS	Small	0.4 s	Degrades	Low
Hybrid (Local)				
VU and Frequency Set-Point	Small	0.15-0.21 s	Slightly degrades	Low
Hybrid Sandia Frequency Shift and $Q\!-\!f$ Method	Small	1.4 s	Slightly degrades	None
Remote				
PLCC	None	200 ms	None	None
SPD	None	100-300 ms	None	None
SCADA	None	Slow for busy systems	None	None
Modified IDMs				
PAOSV	None	0.10 s	No	Low
PADSI	None	< 2 s	Minimal	Low
PMU	Small	< 2 s (300 ms)	Slightly degrades	Low
VU and Reactive Power Change with Positive Feedback	None	< 2 s (0.445 s)	Slightly degrades	Low
ROCOVU-WT	None	< 2 s	No	Low
Reference Current Disturbance	Small	< 2 s (300 ms)	No	Low
VMD based approach	None	< 2 s (0.06 s)	Minimal	Low
SGWT and MODWT-based approach	None	< 2 s (0.3 s)	No	Low

V. Conclusion

The review of various islanding detection methods for microgrids/DGs has been done in this paper. The local, remote and other approaches have been briefed about the performance evaluation of important indices namely NDZ, DT, ED rate and PQ. The use of signal processing/decomposition for passive methods opens the new direction for further investigations to observe hidden insights of the signal useful for islanding detection. The findings of these study may be used to inform the selection of islanding detection methods for specific applications that ensures the safety and reliability of the grid.

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