scientific reports

Check for updates

OPEN

Robust modified passive islanding detection for microgrids using mathematical morphology based dual algorithm

Fayez F. M. El-Sousy[1]✉, Nauman Ali Larik[2,3], Wei Lue[2], Sulaiman Z. Almutairi[1], Mohammed H. Alqahtani[1] & Saleh Mobayen[4]

The integration of distributed generation (DG) in microgrids has brought the challenge of islanding detection, where a portion of the grid operates independently due to disconnection from the main utility. Traditional islanding detection methods often struggle to balance detection speed, reliability, and non-detection zones (NDZ). This paper presents a novel modified passive islanding detection strategy based on a mathematical morphological filter (MMF) with a sliding window method-based median filter (SWMBMF), designed to address these challenges in microgrid systems. The measured noisy voltage signal at point of common coupling (PCC)/DGs-terminal is initially estimated via SWMBMF by continuously monitoring the signals with minimal latency. Then, the MMF is utilized to process the estimated voltage to compute the voltage residuals index (VRI). Moreover, the VRI are compared with pre-specified threshold setting to detect islanding conditions, VRI also effectively distinguishes between normal and islanding conditions. Comprehensive MATLAB/Simulink 2023b simulations demonstrate the robustness of the proposed strategy under various islanding scenarios and grid disturbances, proving its effectiveness in ensuring the stability and reliability of microgrid operations. The proposed method demonstrates an impressive accuracy of 99%, successfully identifying islanding events within 5 ms. This rapid detection enhances grid reliability and minimizes risks associated with delayed islanding detection. The proposed scheme has negligible non detection zone (NDZ).

Keywords Islanding detection, Mathematical morphological filter, Passive methods, Non-detection zone

Motivation and incitement

The increasing integration of DG systems, such as solar photovoltaics and wind turbines, into grid-tied distribution networks, presents several operational challenges, with islanding detection being one of the most critical[1]. Islanding occurs when a portion of the grid continues to be powered by local DG sources even after disconnection from the main utility grid[2]. Failure to detect islanding promptly can result in equipment damage, safety hazards, and operational instability[3]. Various islanding detection techniques have been developed to address this, including passive, active, and hybrid methods.

Literature review

Passive techniques monitor system parameters such as voltage, frequency, and harmonic distortion at the PCC to detect islanding conditions[4]. They are simple and non-intrusive but often suffer from a large NDZ, making them less reliable for detecting islanding in certain scenarios[5]. Some passive schemes were reported in the literature. Authors in[6] proposed the modified passive islanding detection scheme using the One-dimensional recursive Median filter algorithm to effectively detect islanding and non-islanding incidents in a grid-tied distributed generation network. The proposed passive islanding detection scheme[7], was based on the phase angle of positive sequence voltage, which effectively discriminated islanding from non-islanding events within 0.10 s. Second

[1]Department of Electrical Engineering, College of Engineering, Prince Sattam Bin Abdulaziz University, Al-Kharj 16273, Saudi Arabia. [2]Chang Yuan Contron Power Safety Technology Company Ltd., Zhuhai 519085, People's Republic of China. [3]School of Electric Power Engineering, South China University of Technology, Guangzhou 510641, People's Republic of China. [4]Graduate School of Intelligent Data Science, National Yunlin University of Science and Technology, 123 University Road, Section 3, Douliou, Yunlin 640301, Taiwan. ✉email: f.elsousy@psau.edu.sa

Generation Wavelet Transform and Maximum Overlap Discrete Wavelet Transform were utilized to propose passive islanding detection[8], which detected all types of islanding, even with zero power mismatch. The authors proposed a voltage control method for passive islanding detection[3] using reactive power and an artificial neural network, detecting islanding events rapidly and accurately in medium voltage multi-microgrid systems. The proposed passive islanding detection algorithm[9], based on analyzing DC-link voltage in photovoltaic inverters, effectively detected islanding on low and medium voltage scales. RMS voltage and frequency indices processed through peak and valley analysis in the proposed scheme[10], demonstrated superior accuracy and faster detection in simulations and real-time hardware tests across various modes.

Active techniques, on the other hand, intentionally perturb the system by injecting small disturbances, such as frequency or reactive power shifts, to force changes in the grid's operating condition. While these methods improve detection accuracy by reducing the NDZ, they can negatively affect power quality and increase system complexity[11]. Some active methods were also reported in previous literature. The established islanding detection method[12], utilizing voltage-to-current ratio constancy in response to step changes in active power reference, effectively differentiated between grid faults requiring low voltage ride-through and actual islanding. Authors in[13] Utilized d-axis current injection and a novel hybrid analyzing technique accurately and rapidly to distinguish between islanding and non-islanding events in microgrids. A predefined pattern of periodic step changes in active power was utilized in[14], achieved zero NDZ by maintaining a constant ratio of d-axis voltage to d-axis current, with successful simulation and experimental validation for both single and multiple inverters. Negative-sequence current injection was utilized in[15] For successful detection of islanding conditions in microgrids. The authors in[16], the proposed Negative Sequence Current Injection-based protection scheme accurately detected high impedance faults in islanded microgrids without requiring communication, as demonstrated through systematic simulation-based validation under various fault types and conditions.

Hybrid techniques combine elements of both passive and active methods to strike a balance between accuracy and system impact, offering a compromise between non-intrusiveness and reliability[17]. Some hybrid methods were also proposed in prior literature. The hybrid islanding detection method was proposed for grid-connected microgrids with multiple inverter-based distributed generators that effectively combined passive and active techniques, utilizing reactive power disturbance and adaptive disturbance slope adjustments[18]. Another hybrid islanding detection technique was proposed in[19], utilizing Lissajous pattern analysis and battery energy storage system control, achieved enhanced reliability and sensitivity and effectively addressed uncertainties in various real-time scenarios using the Typhoon-HIL tool. The hybrid islanding scheme was proposed in[20], utilizing a smart classifier to select active techniques as needed, demonstrated accuracy, robustness, and rapid detection without degrading power quality. The hybrid islanding detection strategy was proposed in[21], combining Sandia Frequency Shift and Rate of Change of Frequency Relay with Maximum Likelihood estimation, demonstrated a response time nearly three times faster than the Phase-Locked-Loop method and improved detection sensitivity and accuracy in simulations. The two-staged islanding detection technique was proposed in[22], combining Lissajous pattern analysis, and a battery unit-based inverter, achieved fast and accurate detection by addressing power quality issues and enhancing reliability, as demonstrated through real-time experiments with Typhoon-HIL tools.

Limitations of existing work

Authors in prior research tried to address islanding but existing islanding detection methods have still some limitations as follows.

1. Many existing islanding detection methods suffer from high computational latency, which can delay the detection process and reduce the effectiveness of the protection scheme, particularly in real-time applications.
2. Some existing schemes are very exorbitant due to the utilization of high-cost devices like phasor measurement units (PMUs).
3. Few schemes have very large NDZ and are less accurate. Moreover, some schemes are very slow in detecting the islanding events.
4. Some existing scheme fails to work under the noisy measurement conditions in dynamic non-linear microgrid environment.

Contributions and paper organizations

In our proposed method, we have designed a modified passive detection scheme that leverages advanced signal processing techniques, specifically a combination of the MMF and a SWMBMF. This modification allows for rapid and precise islanding detection without the drawbacks of active perturbations, making it a significant improvement over traditional passive technique, and hybrid schemes. These are some prominent contributions of the proposed method.

1. The proposed modified passive islanding detection scheme has very low computational complexity as compared to some existing machine learning and some signal processing-based schemes.
2. The proposed scheme is a very low-cost solution for islanding detection problem because it does not require any high-cost device like PMUs for parameter acquisition.
3. The main contribution of the proposed work is the novel hybrid utilization of MMF with a SWMBMF in time and frequency domain for islanding detection to achieve multiple benefits in term of high accuracy, low computation and rapid detection. We considered a total of 100 test cases, ensuring a diverse range of scenarios that reflect real-world operating conditions. The results demonstrated that our method achieves a detection accuracy of 99%, along with 5 ms detection time.

4. Robust islanding detection index which is capable of detecting islanding events and differentiating it from non-islanding events with reduced NDZ.
5. The proposed scheme deals with noisy measurement conditions.

The structure of the remaining paper is as follows: Sect. 2 presents the mathematical model of the proposed modified passive islanding detection method. Section 3 outlines the stepwise methodology employed in the proposed method. The simulation results and discussions are depicted in Sect. 4. In Sect. 5, a comprehensive comparative assessment of the proposed method against existing benchmarks is provided. Finally, Sect. 6 encapsulates the paper's conclusions.

Mathematical modeling of the proposed method

The mathematical and theoretical background of the proposed scheme is explained in this section which comprises as follows. Dynamic and non-linear microgrid characteristics of microgrids, state-space modeling, MMF and SWMBMF background theory and modeling, voltage residuals index calculations, and threshold level setting.

Dynamic and non-linear microgrid characteristics

Microgrids exhibit dynamic and non-linear characteristics due to their reliance on distributed energy resources (DERs) such as solar photovoltaics, wind turbines, and battery storage systems[23]. These resources introduce variability and uncertainty into the microgrid, as their output depends on factors like weather conditions, load fluctuations, and energy storage levels. The dynamic nature of microgrids is further complicated by the frequent switching between grid-connected and islanded modes of operation, resulting in constantly changing power flows, voltage profiles, and frequency stability. Non-linear behaviors arise from the interaction of power electronic interfaces used in DERs, which can introduce harmonics, voltage distortion, and other non-linear effects into the system[24,25]. Additionally, the control systems of microgrids, including voltage regulators, inverters, and frequency controllers, often exhibit non-linear responses to changes in grid conditions, complicating the prediction and control of system behavior. These dynamic and non-linear characteristics pose significant challenges for maintaining grid stability, requiring advanced control and protection strategies to ensure reliable operation. The measured voltage is equated as follows.

$$\boldsymbol{v_n} = \boldsymbol{V}\mathbf{sin}\boldsymbol{\omega}_0 \tag{1}$$

where v_n depicts the measured voltage at the nth sample. This signal contained some measured and arbitrary noise which affects the protection relay setting. The MMF and SWMBMF-based scheme required a discrete signal to proceed with state estimation. Therefore, the trigonometric derivative of Eqs. (1) is taken and the new transformed equation in one dimension is as follows.

$$v_n = \sum_{n=1}^{N} \overline{v}_n sin\left(wt_n + \varnothing_n\right) + \varepsilon_n \tag{2}$$

where ε_n depicts the random noise.

State-space modelling

The measured discrete voltage signal proceeds for the further state estimation process. However, for the considered dynamic & non-linear microgrid, the state-space & discrete version is.

$$v_n = F\left(v_n\right) + w_n \tag{3}$$

And

$$z_n = h\left(i_n\right) + b_n \tag{4}$$

This state-space & discrete version is utilized to compute the VRI from the voltage signal required in Eqs. (1) to (2) The voltage state vector is equated as.

$$v_n = \begin{bmatrix} v_n \cos\left(w_n + \varnothing_n\right) \\ v_n \, cos\left(w_n + \varnothing_n\right) \\ . \\ . \\ v_k \, cos\left(kgw_n + \varnothing_n\right) \\ v_k \, cos\left(kgw_n + \varnothing_n\right) \\ v_{AC} \\ v_{AC} \propto AC \end{bmatrix} \tag{5}$$

The magnitude of the voltage signature is v_k and the dimension of the matrix is $k \times 1$, while the state transition matrix is.

$$v_n = \begin{bmatrix} v_n\,cos\,(w_n) & -\overline{v}_n\,cos\,(w_n) & 0 & . & 0 & 0 & 0 & 0 \\ \overline{v}_n\,cos\,(w_n) & \overline{v}_n\,cos\,(w_n) & 0 & . & 0 & 0 & 0 & 0 \\ 0 & 0 & \ldots & \ldots & 0 & 0 & 0 & 0 \\ 0 & 0 & \ldots & \ldots & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & \overline{v}_n\,cos\,(w_n) & \overline{v}_n\,cos\,(w_n) & 0 & 0 \\ 0 & 0 & . & 0 & v_n\,cos\,(w_n) & v_n\,cos\,(w_n) & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & -n\delta t \end{bmatrix} \tag{6}$$

The matrix of measurement is denoted as

$$H = \begin{bmatrix} 1 & 0 & 1 & 0 & \ldots & \ldots & 1 & -n\delta t \end{bmatrix} \tag{7}$$

SWMBMF and MMF background theory and modelling

The SWMBMF is a statistical signal processing tool commonly used for noise reduction and outlier removal. Unlike linear filters, which average signal values, the SWMBMF selects the median value within a sliding window, making it robust against impulse noise and signal disturbances. The filter works by moving a fixed-size window across the input signal, calculating the median for each windowed segment, and producing an output that preserves important signal features while mitigating noise[24]. The SWMBMF is particularly useful for preserving edges and sudden changes in the signal, such as the ones encountered during islanding events in grid-tied systems. Its non-linear nature allows for effective separation of the islanding-induced signal deviations from regular grid noise. By using residuals computed through the SWMBMF, the detection of islanding can be achieved with high accuracy, as the filter isolates significant deviations in grid parameters. This robustness and ability to handle non-Gaussian noise make SWMBMF an ideal choice for real-time protection schemes in dynamic environments like microgrids[6]. Figure 1 depicts the estimated and measured voltage signals. The estimated voltage signal provided by SWMBMF is as follows.

$$\widehat{V_e} = V_n + \varnothing \tag{8}$$

V_e is the estimated voltage from the corresponding faulty bus. while V_n is the magnitude of the estimated voltage. However, $\varnothing$ depicts the random error or white Gaussian noise. Then, the estimated voltage is provided to MMF for VRI computation. Figure 1 depicts the steps of the SWMBMF algorithm.

MMF is a non-linear signal processing technique rooted in set theory and widely used for analyzing geometrical structures within signals. Originally developed for image processing, MMF has found applications in various fields, including power systems, due to its ability to extract relevant features while suppressing noise[23]. The core operations in MMF are dilation and erosion, which modify the shape of the signal by expanding or contracting its structure, respectively. When combined, these operations lead to opening and closing filters, which smooth signals and highlight important transitions without distorting the fundamental shape of the waveform. In the context of microgrid islanding detection, MMF can be applied to filter voltage or current waveforms to detect abrupt changes, such as those caused by islanding events, while eliminating high-frequency noise or

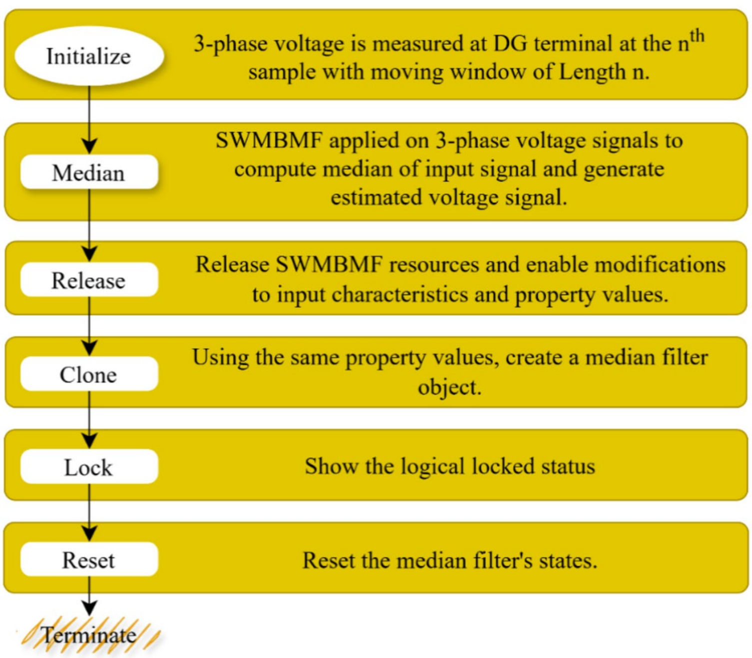


Fig. 1. Steps of SWMBMF algorithm.

transient disturbances[26]. MMF's capability to handle non-linearities and local variations makes it particularly effective for analyzing dynamic signals in complex power networks. The SE for the electrical signal is as follows.

$$\Upsilon_{dil} = \max_{0 \le n-m \le n} \{f(n-m) + g(m)\} \tag{9}$$

$$\Upsilon_{ero} = \min_{0 \le n+m \le n} \{f(n+m) + g(m)\} \tag{10}$$

Here Υ_{dil} and Υ_{ero} represent dilated and eroded signals respectively. Furthermore, f is a signal to be dilated or eroded, whereas g is SE.

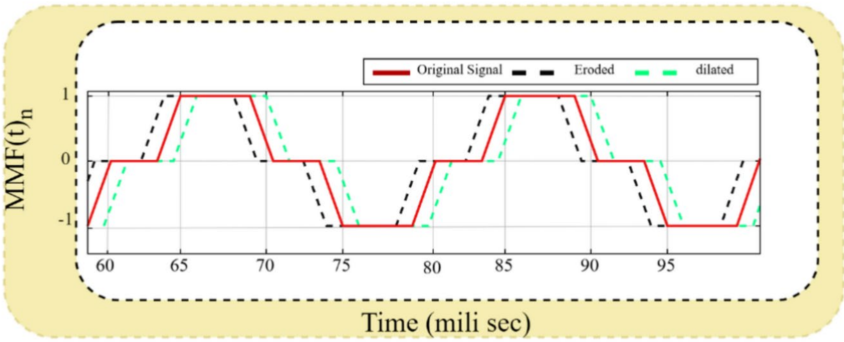
$$\Upsilon_{open} = (fog_n) \tag{11}$$

$$\Upsilon_{open} = (f.g_n) \tag{12}$$

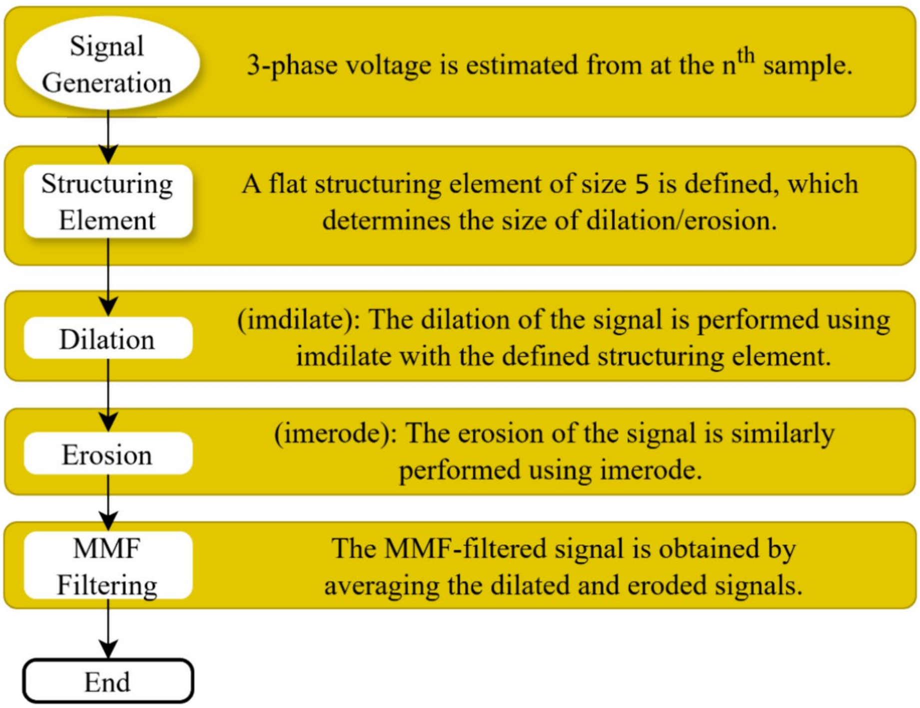
Opening and closing operations of "f" by "g" denoted by "fog" and "$f{\cdot}g$" respectively. Figure 2a depicts the dilated and eroded signals of MMF, whereas Fig. 2b highlights the Steps of MMF algorithm.

VRI calculation

In VRI calculation, the MMF is applied to the voltage signal to eliminate spikes and outliers, ensuring a smooth and reliable signal for further analysis. The VRI is then computed by comparing the filtered voltage signal with a



(a)



(b)

Fig. 2. (**a**) Original, Dilated, and eroded signal of MMF algorithm. (**b**). Steps of MMF algorithm.

reference value, typically the nominal or rated voltage. The difference between the actual and reference voltages indicates the degree of voltage regulation required. By leveraging MMF, the VRI calculation becomes more resilient to transient events, noise, and harmonic distortion, leading to more precise voltage control, which is critical in systems with distributed energy resources or variable loads. This method provides a robust tool for real-time monitoring and control, enhancing the stability and efficiency of power distribution networks. The computed VRI is as follows:

$$VRI = \widehat{V}_e - v_n \tag{13}$$

Proposed islanding detection strategy

The proposed islanding detection scheme is depicted in Fig. 3. The first step in our proposed islanding detection methodology involves the continuous monitoring of voltage signals from DG systems within the microgrid. Voltage measurements are taken at the PCC to capture the dynamic behavior of the grid. These signals often contain noise due to the inherent variability of renewable energy sources, grid disturbances, and electrical equipment. To ensure real-time monitoring with minimal latency, the sliding window method is applied. This method estimates the true voltage by continuously analyzing small, overlapping sections (windows) of the voltage signal. The sliding window helps to smooth out random fluctuations while preserving critical changes in the signal that may indicate an islanding event. This process ensures that even minor disturbances or rapid transitions in the grid can be captured and evaluated.

After the initial monitoring, the measured voltage signals are further processed using a SWMBMF. The purpose of the SWMBMF is to reduce noise and filter out transient disturbances that could lead to false detections. By moving a fixed-size window across the voltage data, the median value within each window is computed and used to represent the true signal for that segment. This technique is highly effective in mitigating the effects of outliers and impulse noise, which are common in microgrid environments. Importantly, the SWMBMF preserves critical signal features, such as sudden changes caused by island, ensuring that the essential characteristics of the voltage signal remain intact for further analysis.

Once the voltage signal has been preprocessed, the next step is to apply the MMF to compute the VRI. MMF is a non-linear filtering technique that is particularly well-suited for identifying changes in the structure of a signal. In this step, we leverage MMF's ability to isolate key signal transitions, such as those resulting from islanding events. By performing morphological operations like dilation and erosion, the MMF extracts the underlying

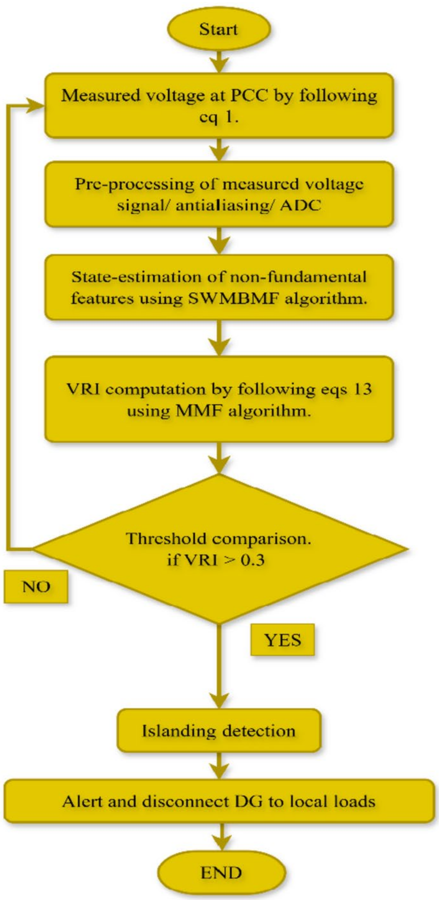


Fig. 3. Flow chart of the proposed islanding detection scheme.

geometrical features of the voltage signal. This process results in a set of residuals that represent the deviation of the observed voltage from its expected value under normal grid conditions. The computed VRI serves as a key indicator for distinguishing between normal operating conditions and islanding scenarios.

The VRI computed through MMF is then compared against a predefined threshold to detect islanding events. If the VRI exceeds the threshold, it indicates that a significant deviation has occurred, suggesting that the microgrid has been islanded. The choice of the threshold is crucial; it must be set high enough to avoid false positives from minor disturbances but low enough to ensure that islanding is detected promptly. In our methodology, we fine-tuned the threshold based on simulations and real-world data to achieve a high level of accuracy. The system is capable of identifying islanding events within 5 ms, significantly enhancing grid reliability by allowing for rapid disconnection or corrective actions when necessary.

Testing and validation of the proposed scheme

Standard microgrid test beds

IEEE-13 bus microgrid test bed

The IEEE-13 bus microgrid test bed is widely used in power system research for validating various protection schemes, including islanding detection mechanisms. This testbed represents a portion of a typical distribution network, integrating various DERs such as 1-photovoltaic-based DG and 1-wind turbines-based DG. The IEEE-13 bus microgrid provides a suitable environment for testing advanced detection algorithms under real-world operational scenarios, such as varying load conditions, DER outputs, and balanced/unbalanced load and generation conditions[6]. The single line diagram of IEEE test system is depicted in Fig. 4a. There are three islands simulated in the proposed scheme. The data of the proposed system is taken from ref.

UL-1741 microgrid test bed

The UL-1741 standard is widely used for testing the anti-islanding performance of inverters in grid-tied microgrids. A microgrid test bed based on this standard provides a controlled environment for evaluating the NDZ in islanding detection schemes. In the proposed scheme, the UL-1741 test bed allows for precise simulation of islanding conditions, where the performance of various detection algorithms can be rigorously tested. By analyzing the NDZ, researchers can quantify the scheme's ability to accurately detect islanding events under diverse load and generation scenarios. The smaller the NDZ, the more effective the scheme, ensuring enhanced protection for the microgrid during unintentional islanding situations[6]. The single line diagram of UL-1741 test system is depicted in Fig. 4b while the current control circuitry of UL-1741 is depicted in Fig. 4c.

Results and discussions

We validated the proposed scheme using comprehensive simulations in MATLAB/Simulink 2023b. Various islanding and non-islanding scenarios were simulated to test the robustness and reliability of the method on standard IEEE and UL-1741 test beds. These simulations included conditions such as islanding and non-islanding. The results demonstrated that our method achieved an accuracy of 99%, effectively detecting islanding events with minimal false detections. By processing the voltage signal in real time and distinguishing between normal and islanding conditions, the proposed strategy offers a reliable and computationally efficient solution for microgrid protection. The success of the simulations underscores the practical applicability of the methodology for real-world microgrids, ensuring stable and reliable operations. Different case studies are presented here to validate the efficacy of the proposed method. The SWMBMF combined with the mathematical morphological filter inherently provides robustness against harmonic distortion, as it focuses on residuals and avoids directly relying on the signal's harmonic content.

Islanding cases

Wind-based DG islanding detection

Several such cases were conducted to evaluate the proposed islanding detection method under unbalanced load and generation conditions in a wind-based DG system. Using MATLAB/Simulink 2023b, a grid-tied microgrid with wind-based DG was simulated, where intentional imbalances were introduced between load demand and generation output. These conditions are challenging due to the fluctuating nature of wind energy and the mismatch between generation and consumption, which could potentially mask islanding events. Several such cases were simulated but due to lack of space one is depicted here. An islanding event at island − 2 is generated at 0.25 milli seconds by disengaging wind-based DG through switching circuit breaker R-45. As illustrated in Fig. 5 the VRI in this case is more than the predefined threshold value during the occurrence of an islanding event. This indicates the successful operation of the proposed scheme during the islanding event in wind-based DGs and under unbalanced load and generation conditions.

PV-based DG islanding detection

Several such cases were conducted to assess the performance of the proposed islanding detection method in a PV-based DG system under balanced load and generation conditions. Using MATLAB/Simulink 2023b, a grid-connected PV-based microgrid was simulated with equal load demand and generation output, representing an ideal operating scenario in the IEEE test bed. The balanced condition poses a challenge for many traditional islanding detection methods, as the absence of significant voltage or frequency deviations can lead to a large NDZ. Several such cases were simulated but due to lack of space one is depicted here. An islanding event at island − 3 is generated at 0.3 milli seconds by disengaging PV-based DG through switching circuit breaker R-31. As illustrated in Fig. 6 the VRI in this case is more than the predefined threshold value during the occurrence of

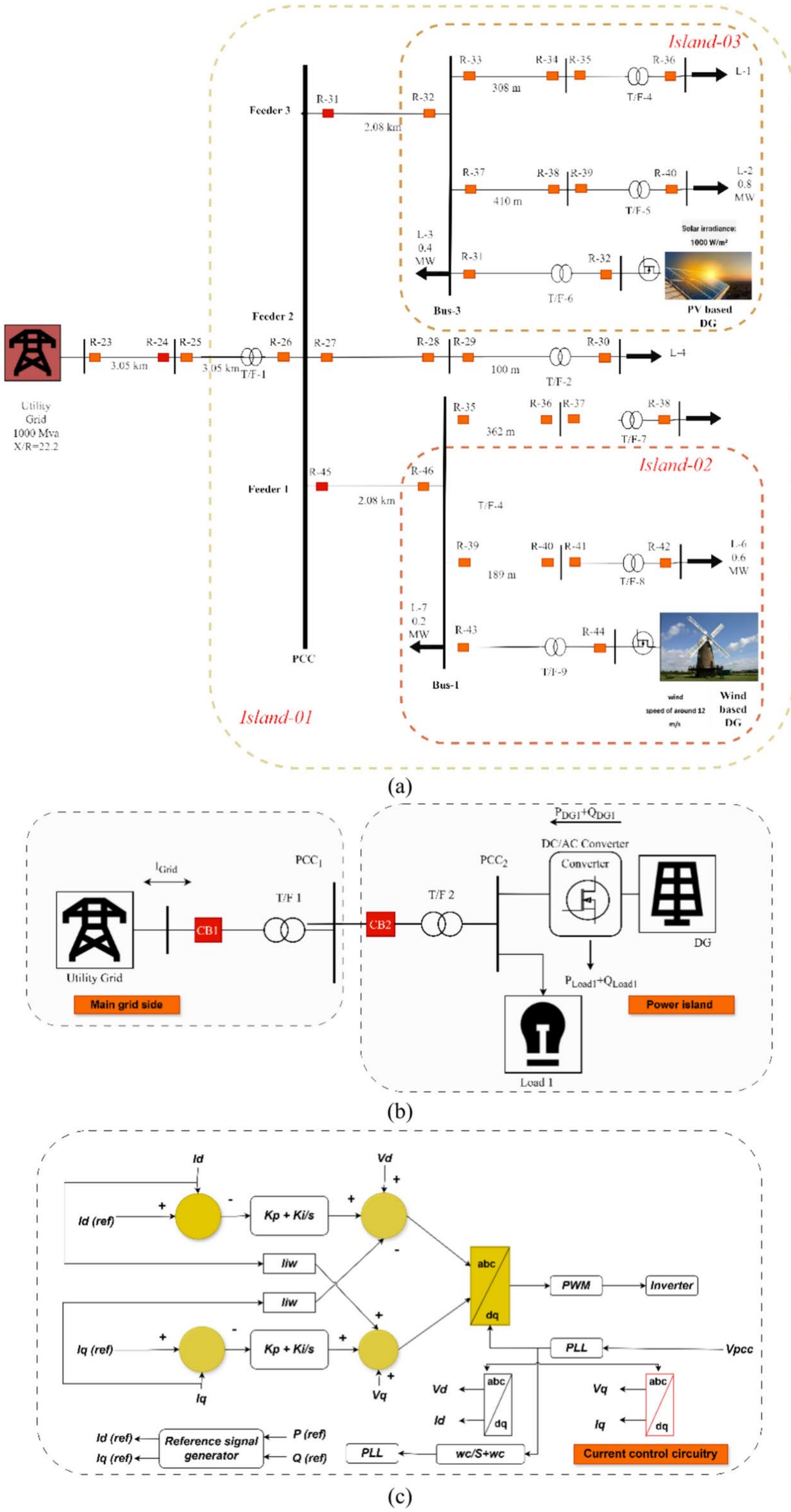


Fig. 4. (**a**) Single line diagram of IEEE test bed. (**b**) UL-1741 test bed. (**c**) Control circuitry of UL-1741.

an islanding event. This indicates the successful operation of the proposed scheme during the islanding event in wind-based DGs and under balanced load and generation conditions.

Non-islanding cases

Capacitor switching case

Capacitor switching is a common grid event that can introduce transient disturbances, often leading to false detections in traditional islanding detection methods. Using MATLAB/Simulink 2023b, we simulated Several

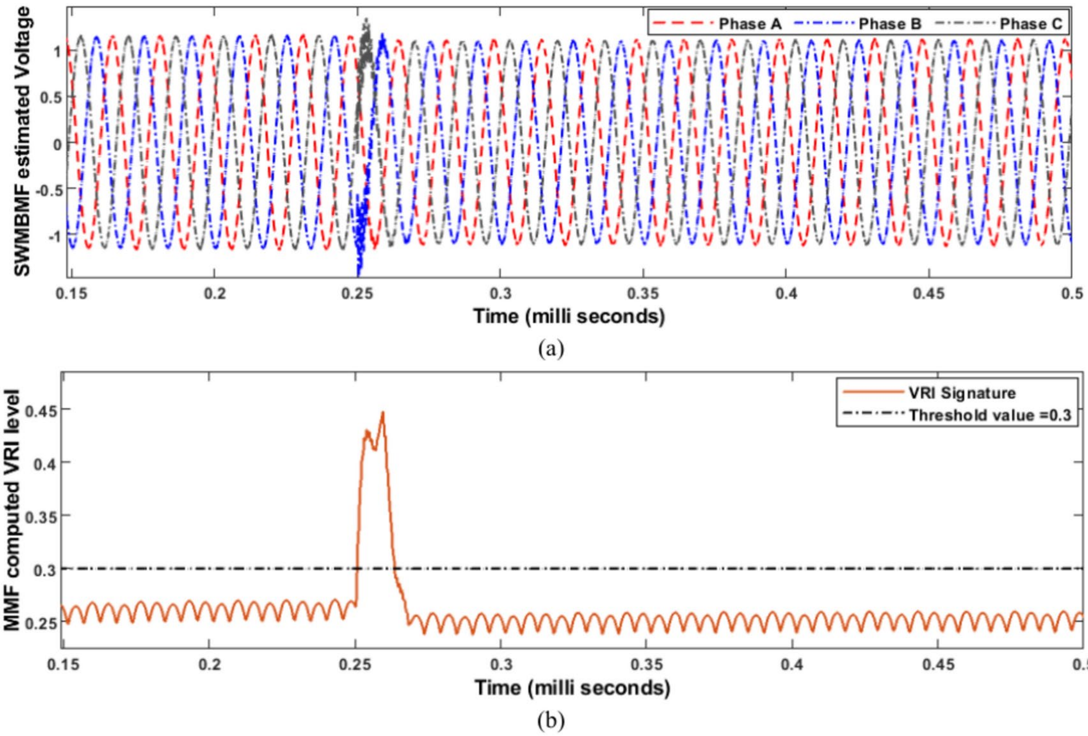


Fig. 5. (**a**) SWMBMF- estimated voltage signature. (**b**) MMF computed VRI in Island-02 case.

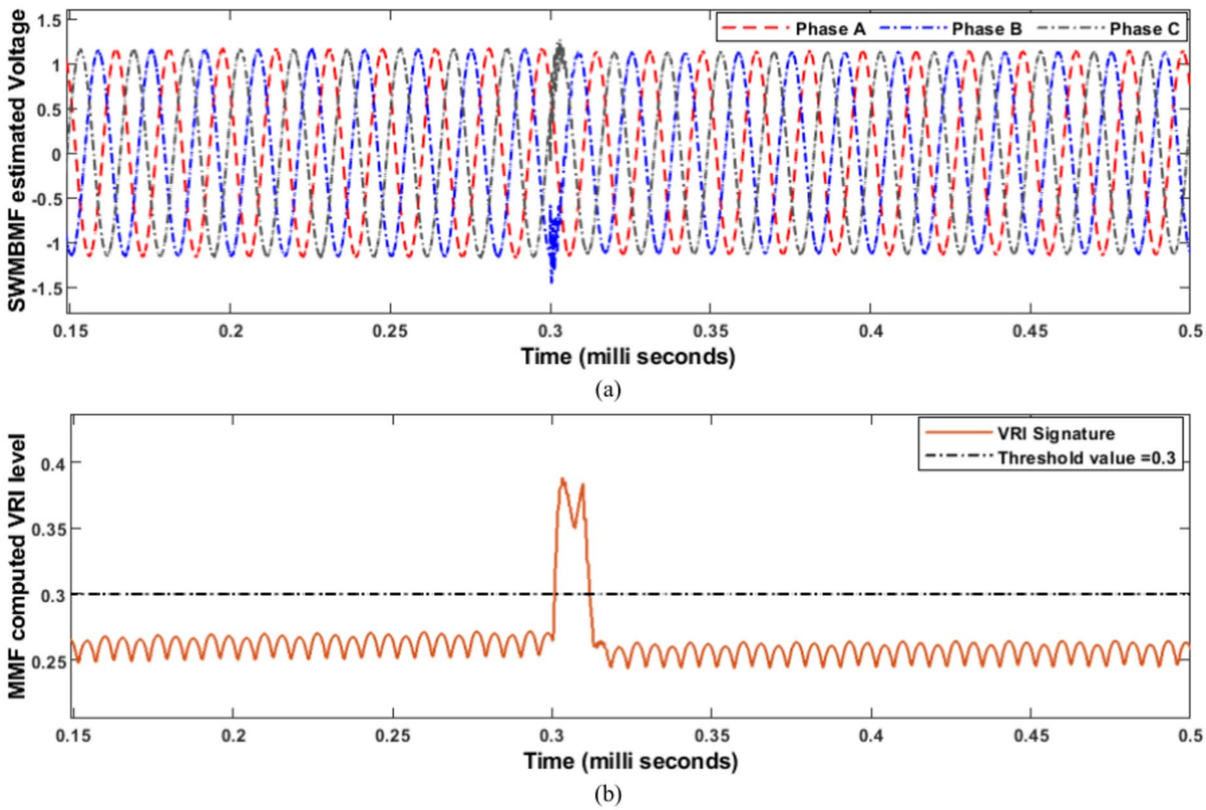


Fig. 6. (**a**) SWMBMF- estimated voltage signature. (**b**) MMF computed VRI in the Island-03 case.

non-islanding events where a capacitor bank was switched in and out of the system to test the sensitivity of the proposed scheme. To evaluate the robustness of the proposed islanding detection method in non-islanding scenarios, several case study simulations were performed under capacitor switching conditions in a grid-tied microgrid. A non-islanding event is generated at 0.2 milli seconds by switching the capacitor bank. As illustrated in Fig. 7 the VRI in this case is less than the predefined threshold value during the occurrence of a non-islanding event. This confirms the accurate detection and differentiation of the proposed scheme's operation during the non-islanding condition.

Heavy load switching case

Several non-islanding case studies were conducted to assess the performance of the proposed islanding detection method under heavy-load switching conditions in a grid-tied microgrid. Heavy-load switching can cause significant voltage fluctuations and transient disturbances, which often lead to false islanding detections in traditional methods. Using MATLAB/Simulink 2023b, a simulation was carried out where a large load was suddenly connected and disconnected from the microgrid to create a challenging non-islanding scenario. A non-islanding event is generated at 0.4 milli seconds by switching heavy load. As illustrated in Fig. 8 the VRI in this case is less than the predefined threshold value during the occurrence of a non-islanding event. This confirms the accurate detection and differentiation of the proposed scheme's operation during the non-islanding condition.

Motor switching case

Several non-islanding case study simulations were performed to evaluate the proposed islanding detection method under motor switching conditions in a grid-tied microgrid. Motor switching events, which can cause sudden changes in current and voltage due to inrush currents, pose a challenge for traditional islanding detection methods by creating transient disturbances that can lead to false positives. Using MATLAB/Simulink 2023b, we simulated the connection and disconnection of an induction motor to test the sensitivity and robustness of the proposed scheme. A non-islanding event is generated at 0.35 milli seconds by switching the inductive motor. As illustrated in Fig. 9 the VRI in this case is less than the predefined threshold value during the occurrence of a non-islanding event. This confirms the accurate detection and differentiation of the proposed scheme's operation during the non-islanding condition.

Comparative analysis

The NDZ is a critical parameter in evaluating the effectiveness of islanding detection schemes, as it represents the range of operating conditions under which an islanding event may not be detected. Therefore, the proposed scheme was compared with their existing benchmark methods, enlisted in Table 1, named as 1st method[19], 2nd

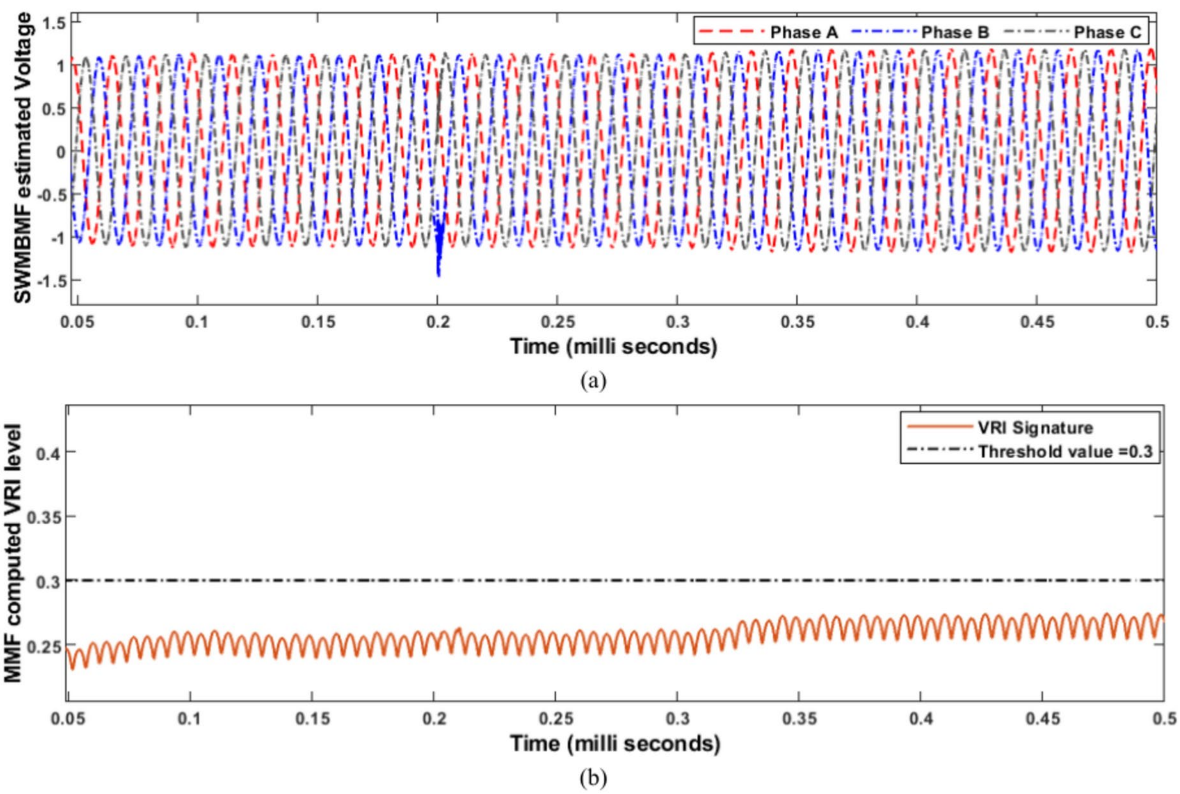


Fig. 7. (**a**) SWMBMF- estimated voltage signature. (**b**) MMF computed VRI in the capacitor switching case.

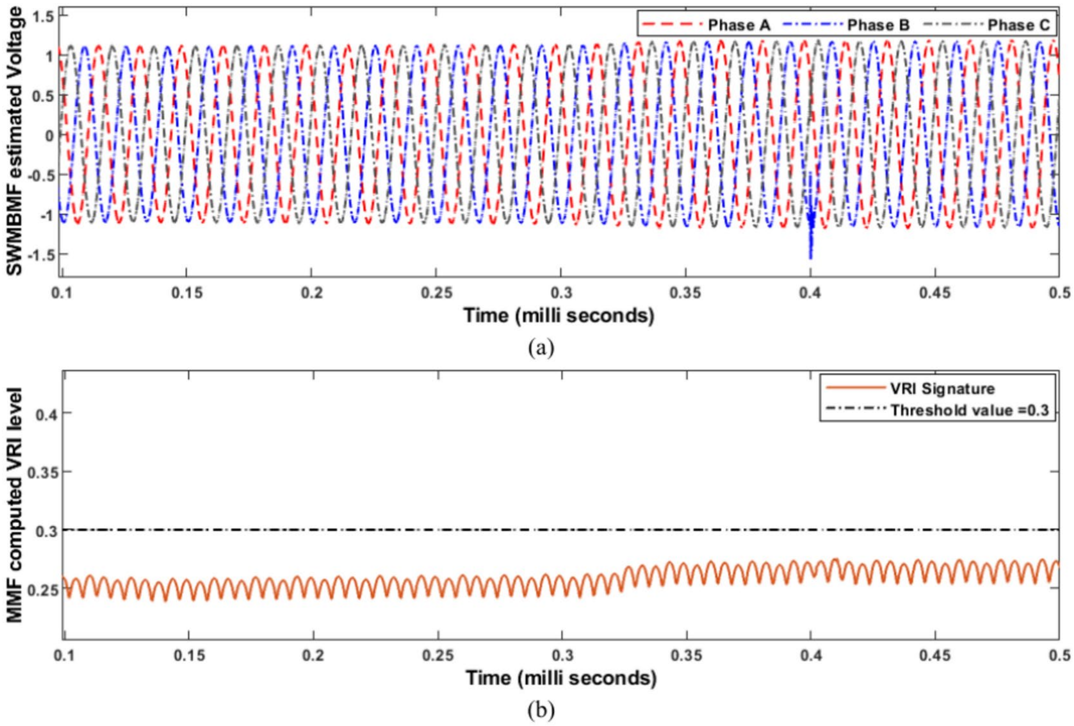


Fig. 8. (**a**) SWMBMF-estimated voltage signature. (**b**) MMF computed VRI in heavy load switching case.

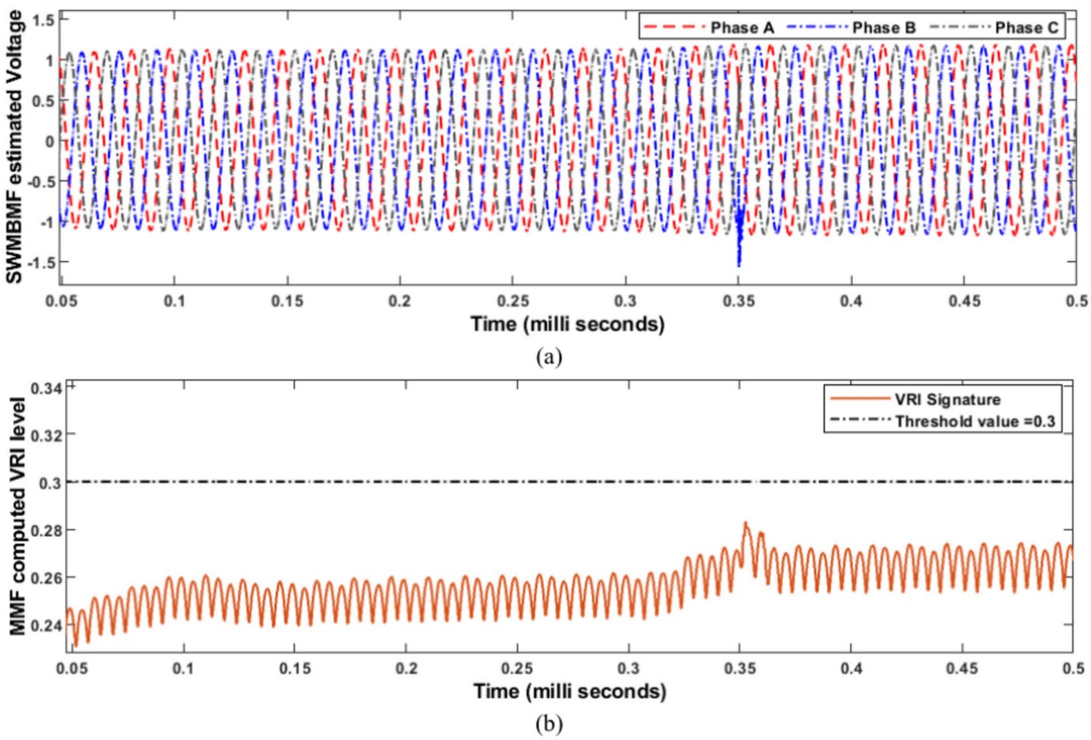


Fig. 9. (**a**) SWMBMF-estimated voltage signature. (**b**) MMF computed VRI in inductive motor switching case.

Comparison Parameters	Compared benchmark Methods				Proposed scheme
	μ-PMUs-based method[28]	Random forest-based method[29]	6G -based method [30]	Cyber-attack protection-based method[31]	
Time of action	20 ms	49 s	52 ms	15 ms	5 ms
Noise consideration	Yes	Yes	Yes	yes	yes
Cost comparison	High cost due to PMUs devices	High cost due to PMUs devices	High cost due to PMUs devices	High cost due to PMUs devices	Low cost
Cyber secured	Yes	Yes	Yes	Yes	Not

Table 1. Comparitive analysis of proposed scheme with some other schemes.

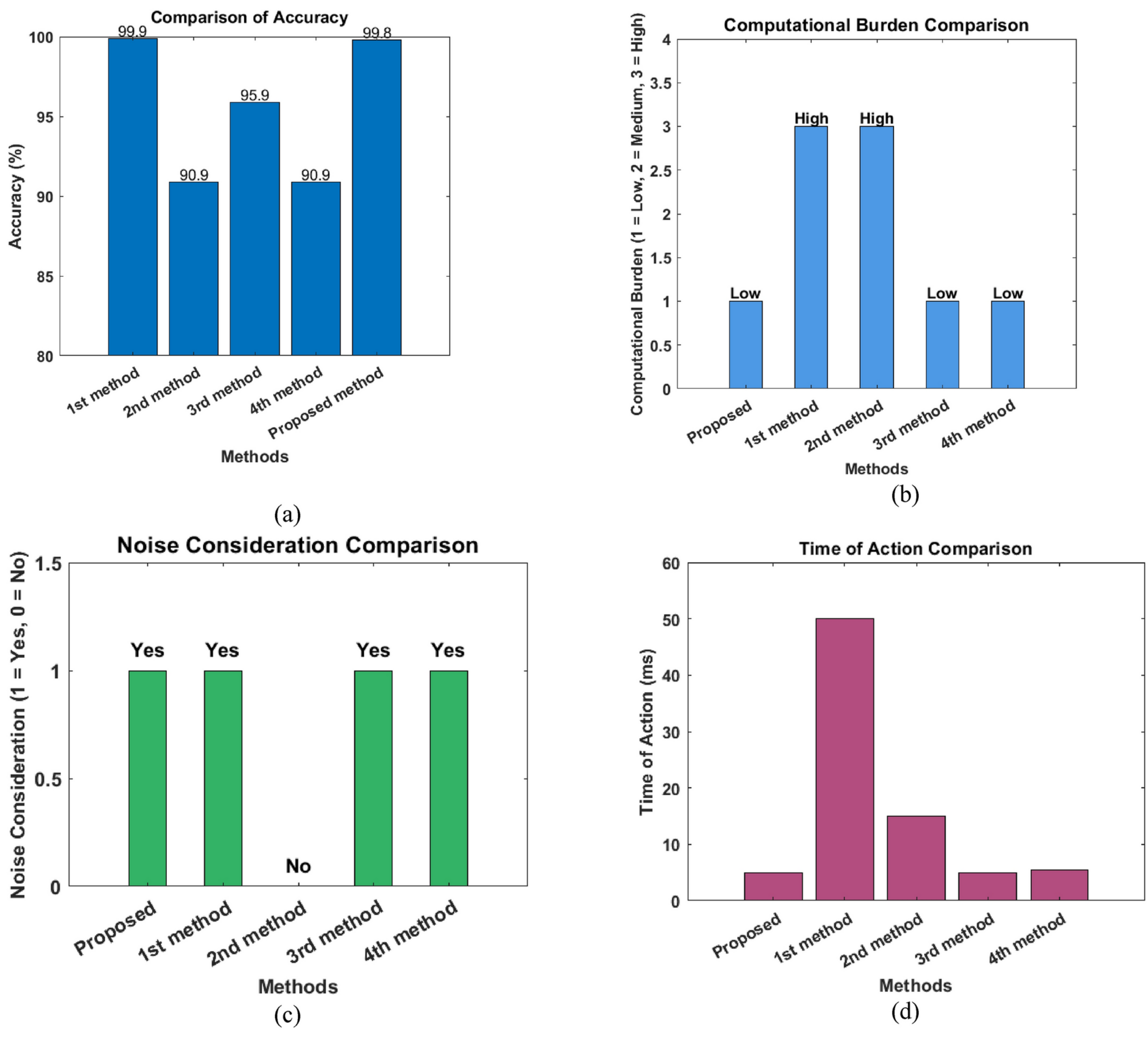


Fig. 10. (**a**) Accuracy comparison, (**b**) Computational burden comparison, (**c**) Noise consideration comparison, and (**d**) Time of action comparison.

method[27], 3rd method[6], 4th method[7], 5th method[28], 6th method[29], 7th method[30], and 8th method[31] in terms of accuracy, time of action, noise consideration, and computational complexity as depicted in Fig. 10.

Computational complexity analysis

The computational complexity analysis evaluates the execution time of the proposed MMF and SWMBMF methods across varying input signal sizes as illustrated in Fig. 11a. Synthetic random signals of different lengths are processed, and the time taken for execution is measured using MATLAB's `tic` and `toc` functions. For MMF, morphological operations such as erosion and dilation are used as part of the filtering process, while for SWMBMF, a sliding window-based moving median filter is applied. The analysis demonstrates how the execution

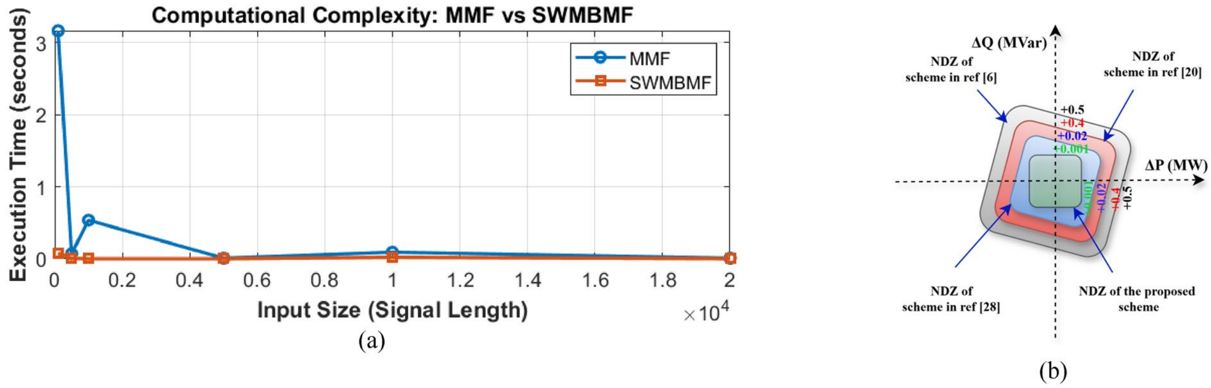


Fig. 11. **(a)** Computational complexity analysis of the proposed algorithms. (**b**) NDZ analysis.

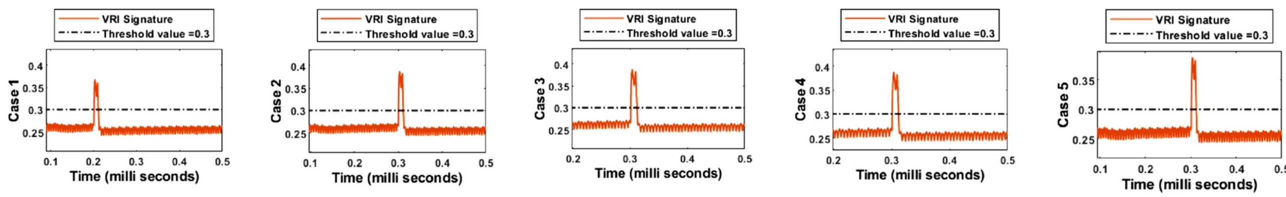


Fig. 12. NDZ analysis on UL-1741 test results on different load variations.

time changes with increasing signal length, with results plotted to compare the computational performance of both methods. The findings highlight the low computational complexity of the proposed approaches, as indicated by their modest increase in execution time even for large input sizes. This validates the efficiency and scalability of MMF and SWMBMF, making them suitable for real-time applications.

NDZ analysis

The NDZ comparison with the existing method is very important to evaluate the performance of any method[32]. The comparison of power mismatch after NDZ analysis is illustrated in Fig. 11b. The NDZ analysis and testing of the proposed islanding detection scheme were conducted using the UL-1741 test bed, a standard framework for evaluating anti-islanding techniques as illustrated in Fig. 12. The NDZ represents the range of operating conditions, such as power mismatches and load variations, where the detection scheme might fail to identify an unintentional islanding event. To ensure comprehensive evaluation, the test cases included scenarios with varying power mismatches (0–5%) and load variations, simulating realistic grid conditions. The proposed scheme demonstrated an exceptionally low NDZ, reliably detecting islanding events across all tested scenarios. This performance can be attributed to the robustness of the MMF and SWMBMF-based signal processing methods, which effectively distinguish islanding conditions from normal grid disturbances. The results confirm the capability of the scheme to maintain high accuracy, even under challenging conditions, while adhering to the requirements of UL-1741 standards. This highlights the suitability of the proposed approach for deployment in modern distributed energy systems with high reliability.

Conclusions

In conclusion, the proposed modified passive islanding detection strategy, utilizing an MMF with an SWMBMF, offers a highly effective solution to the challenges posed by islanding detection in microgrids. The strategy successfully addresses key issues related to detection speed, reliability, and NDZ, providing rapid identification of islanding events in less than 5 ms with an impressive accuracy of 99.8%. Simulations conducted in MATLAB/Simulink 2023b confirm the robustness of the method under various islanding scenarios and grid disturbances. This approach significantly enhances the stability and reliability of microgrid operations, minimizing risks associated with delayed detection and ensuring efficient system performance.

As a future work we incorporate Low Voltage Ride-Through (LVRT) and High Voltage Ride-Through (HVRT) capabilities into the proposed islanding detection scheme for wind-based distributed generation (DG) sources. A harmonic filtering stage could be integrated to further enhance the method's performance under high harmonic distortion.

Data availability

All data generated or analyzed during this study are included in this published article.

Received: 1 November 2024; Accepted: 3 February 2025

Published online: 20 February 2025

References

1. Barkat, F. et al. Review, analysis, and performance evaluation of the most common four active methods for islanding detection in grid-connected photovoltaic systems. *Electr. Power Syst. Res.* https://doi.org/10.1016/j.epsr.2022.108909 (2023).
2. Larik, N. A., Ahmed, M., Zhang, L. L., Jamali, J. A., & Wu, Q. H. A New Method of Unintentional Islanding detection for Multiple Distributed energy resources based Power System. In *2023 4th International Conference on Computing, Mathematics and Engineering Technologies (iCoMET)* 1–6 (IEEE, 2023). https://doi.org/10.1109/iCoMET57998.2023.10099374.
3. Vadlamudi, B. & Anuradha, T. Review of islanding detection using advanced signal processing techniques. *Electr. Eng.* https://doi.org/10.1007/s00202-023-01967-4 (2023).
4. Kumar, K., Kumar, P. & Kar, S. A review of microgrid protection for addressing challenges and solutions. *Renew. Energy Focus* https://doi.org/10.1016/j.ref.2024.100572 (2024).
5. Larik, N. A., Tahir, M. F., Elbarbary, Z. M. S., Yousaf, M. Z. & Khan, M. A. A comprehensive literature review of conventional and modern islanding detection methods. *Energy Strategy Rev.* **44**, 101007. https://doi.org/10.1016/j.esr.2022.101007 (2022).
6. Mumtaz, F., Imran, K., Rehman, H. & Bukhari, S. B. A. 1D recursive median filter based passive islanding detection strategy for grid-connected distributed generations network. *IET Renew. Power Gener.* **17**(7), 1731–1746. https://doi.org/10.1049/rpg2.12708 (2023).
7. Shafique, N., Raza, S., Bibi, S., Farhan, M. & Riaz, M. A simplified passive islanding detection technique based on susceptible power indice with zero NDZ. *Ain Shams Eng. J.* https://doi.org/10.1016/j.asej.2021.11.006 (2022).
8. Pangedaiah, B., Reddy, P. L. S. K., Obulesu, Y. P., Kota, V. R. & Alghaythi, M. L. A robust passive islanding detection technique with zero-non-detection zone for inverter-interfaced distributed generation. *IEEE Access* **10**, 96296–96306. https://doi.org/10.1109/ACCESS.2022.3204974 (2022).
9. Elshrief, Y. A., Asham, A. D., Abozalam, B. A. & Abd-Elhaleem, S. A new passive islanding detection technique for different zones in utility grid. *J. Eng. Res. (Kuwait)* **9**(3), 131–143. https://doi.org/10.36909/jer.v9i3B.9699 (2021).
10. Bansal, Y. & Sodhi, R. A statistical features based generic passive islanding detection scheme for IIDGs system. *IEEE Trans. Power Deliv.* **37**(4), 3176–3188. https://doi.org/10.1109/TPWRD.2021.3124986 (2022).
11. Alobaid, M. & Abo-Khalil, A. G. A comprehensive review and assessment of islanding detection techniques for PV systems. *Int. J. Thermofluids* https://doi.org/10.1016/j.ijft.2023.100353 (2023).
12. Sivadas, D., Chithrabhanu, A., Surkod, V. V., Haridas, A. K., & Vasudevan, K. Adaptive active islanding detection strategy enhanced with fault ride-through capability for grid-tied inverters. In *PESGRE 2022—IEEE International Conference on "Power Electronics, Smart Grid, and Renewable Energy,"* (Institute of Electrical and Electronics Engineers Inc., 2022). https://doi.org/10.1109/PESGRE52268.2022.9715832.
13. Murugesan, S. & Murali, V. Hybrid analyzing technique based active islanding detection for multiple DGs. *IEEE Trans. Ind. Inform.* **15**(3), 1311–1320. https://doi.org/10.1109/TII.2018.2846025 (2019).
14. Sivadas, D. & Vasudevan, K. An active islanding detection strategy with zero nondetection zone for operation in single and multiple inverter mode using GPS synchronized pattern. *IEEE Trans. Ind. Electron.* **67**(7), 5554–5564. https://doi.org/10.1109/TIE.2019.2931231 (2020).
15. Bahrani, B., Karimi, H. & Iravani, R. Nondetection zone assessment of an active islanding detection method and its experimental evaluation. *IEEE Trans. Power Deliv.* **26**(2), 517–525. https://doi.org/10.1109/TPWRD.2009.2036016 (2011).
16. Yang, Z., Dyśko, A. & Egea-Àlvarez, A. A negative sequence current injection (NSCI)-based active protection scheme for islanded microgrids. *Int. J. Electr. Power Energy Syst.* https://doi.org/10.1016/j.ijepes.2024.109965 (2024).
17. Larik, N. A., Li, M. & Wu, Q. Triple-indexed passive islanding detection strategy for grid-connected distributed generation networks using an extended Kalman filter. *IET Gener. Transm. Distrib.* **18**(10), 2029–2042. https://doi.org/10.1049/gtd2.13175 (2024).
18. Chen, X., Li, Y. & Crossley, P. A novel hybrid islanding detection method for grid-connected microgrids with multiple inverter-based distributed generators based on adaptive reactive power disturbance and passive criteria. *IEEE Trans. Power Electron.* **34**(9), 9342–9356. https://doi.org/10.1109/TPEL.2018.2886930 (2019).
19. Mondal, S., Gayen, P. K. & Gaonkar, D. N. Battery storage-based novel hybrid islanding detection technique using Lissajous pattern estimation. *IEEE Trans. Instrum. Meas.* https://doi.org/10.1109/TIM.2022.3169527 (2022).
20. Elshrief, Y. A. et al. An innovative hybrid method for islanding detection using fuzzy classifier for different circumstances including NDZ. *J. Radiat. Res. Appl. Sci.* **15**(2), 129–142. https://doi.org/10.1016/j.jrras.2022.04.008 (2022).
21. Biyya, I., Oubrahim, Z. & Abbou, A. Fast hybrid islanding detection for DGs with inverters using maximum likelihood-based ROCOF and SFS. *Comput. Electr. Eng.* https://doi.org/10.1016/j.compeleceng.2024.109176 (2024).
22. Mondal, S., Gayen, P. K. & Gaonkar, D. N. A hybrid islanding detection method based on Lissajous pattern having robust performance under various power quality scenarios. *IEEE Syst. J.* **17**(2), 3005–3015. https://doi.org/10.1109/JSYST.2022.3228800 (2023).
23. Mumtaz, F. et al. Ultra high-speed fault diagnosis scheme for DC distribution systems based on discrete median filter and mathematical morphology. *IEEE Access* **12**, 45796–45810. https://doi.org/10.1109/ACCESS.2024.3381519 (2024).
24. Mumtaz, F., Imran, K., Abusorrah, A. & Bukhari, S. B. A. Harmonic content-based protection method for microgrids via 1-dimensional recursive median filtering algorithm. *Sustainability (Switzerland)* https://doi.org/10.3390/su15010164 (2023).
25. Mumtaz, F., Imran, K., Rehman, H. & Bukhari, S. B. A. Novel protection method for AC microgrids with multiple distributed generations using Unscented Kalman filter. *Electr. Power Syst. Res.* https://doi.org/10.1016/j.epsr.2024.110227 (2024).
26. Shah, M. A. et al. High speed protection of medium voltage DC distribution system using modified mathematical morphology. *IET Renew. Power Gener.* **16**(14), 3134–3148. https://doi.org/10.1049/rpg2.12564 (2022).
27. Abd-Elkader, A. G., Allam, D. F. & Tageldin, E. Islanding detection method for DFIG wind turbines using artificial neural networks. *Int. J. Electr. Power Energy Syst.* **62**, 335–343. https://doi.org/10.1016/j.ijepes.2014.04 (2014).
28. Shukla, Dutta, S., Sadhu, P. K. & Dey, B. An intelligent Island detection scheme to enhance grid resilience. *Microsyst. Technol.* **30**(10), 1363–1379. https://doi.org/10.1007/s00542-023-05602-x (2024).
29. Dutta, S., Olla, S. & Sadhu, P. K. A secured, reliable and accurate unplanned island detection method in a renewable energy based microgrid. *Eng. Sci. Technol. Int. J.* **24**(5), 1102–1115. https://doi.org/10.1016/j.jestch.2021.01.015 (2021).
30. Shukla, Sadhu, P. K., Dutta, S., Sahu, S. K. & Dey, B. An island detection approach in 6G paradigm for an active distribution network—A future perspective for next generation smart grids. *Comput. Electr. Eng.* https://doi.org/10.1016/j.compeleceng.2023.108932 (2023).
31. Shukla, Dutta, S., Sadhu, P. K. & Dey, B. An island detection methodology with protection against cyber attack. *Microsyst. Technol.* **30**(9), 1165–1175. https://doi.org/10.1007/s00542-023-05596-6 (2024).
32. Verma, S., Dutta, S., Sadhu, K., Jaya, M., Reddy, B., & Kumar Mohanta, D. Islanding detection using bi-directional energy meter in a DFIG based active distribution network.

Author contributions

Nauman Ali Larik, Wei Lue, Saleh Mobayen, Mohammed H. Alqahtani and Fayez F. M. El-Sousy: Conceptualization, Saleh Mobayen, Sulaiman Z. Almutairi and Fayez F. M. El-Sousy: formal analysis, Fayez F. M. El-Sousy:

funding acquisition, Saleh Mobayen, Nauman Ali Larik, Wei Lue, Fayez F. M. El-Sousy and Sulaiman Z. Almutairi: investigation, Nauman Ali Larik, Wei Lue, Fayez F. M. El-Sousy, Mohammed H. Alqahtani and Sulaiman Z. Almutairi :methodology, Nauman Ali Larik, Wei Lue, Mohammed H. Alqahtani and Sulaiman Z. Almutairi :writing—original draft, Nauman Ali Larik, Wei Lue, Mohammed H. Alqahtani, Saleh Mobayen and Fayez F. M. El-Sousy: writing—review and editing, and Nauman Ali Larik, Wei Lue, Saleh Mobayen, Mohammed H. Alqahtani and Fayez F. M. El-Sousy: supervision. All authors have read and agreed to the published version of the manuscript.

Funding
The authors extend their application to the Deputyship for Research & Innovation, Ministry of Education in Saudi Arabia for funding this research work through the Project number (IF2/PSAU/2022/01/23085).

Declarations

Competing interests
The authors declare no competing interests.

Additional information
Correspondence and requests for materials should be addressed to F.F.M.E.-S.

Reprints and permissions information is available at www.nature.com/reprints.

Publisher's note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.