Islanding Detection Approach based on Harmonics in Power system Integrated with Multiple DERs

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Abstract- All the Countries worldwide are trying to contribute to environmental protection, including developing green energy and expanding ecological protection. Electrical power has become one of the essential objects of green energy development. Distributed energy sources (DES), i.e., combining renewable energy generation sources and load, can effectively solve the problem of large-scale access to alternative energy and increase the dependability and flexibility of conventional power system. However, DES integration poses serious issues, such as poor power quality, two-way power flow, and unintentional island formation. The islanding of distributed generation (DG) units impacts the maintenance team's safety, which can also harm protective equipment. This paper proposes a passive islanding detection approach (PIDA) for multiple DGs-based power system that uses harmonic contents data to determine islanding conditions. The multiple DER-based Matlab-Simulink environment validates the efficacy of the proposed method by demonstrating a negligible non-detection zone and robust islanding detection in practical scenarios.

Keywords Distributed Generation Non-detection zone, Renewable energy, Unintentional Islanding, Harmonic contents.

1. Introduction

The dispersed green energy generation sector rapidly expands and undergoes technological advancements, and grid-interactive distributed energy resources emerge as necessary empowering technology because of the rising electrical energy consumption worldwide and concern over the depletion of traditional fossil fuels [1]. Substantial commercial growth and technological advancement has principally enhanced the integration of distributed energy systems into traditional electricity networks [2, 3]. The advantages of DG networks include the ability to produce dependable power on-site, which minimizes the need for additional transmission lines and prevents line losses. The energy industry is highly developed and shifting toward decentralization since renewable energy sources benefit the national economy, environment, and security [4]. There are two sorts of DG units in a microgrid system, grid-following DG units and grid-forming DG units which adopt voltage control and current control scheme, respectively [5]. DG units are normally controlled as grid-following during grid integrated state, whereas grid-forming mode is used during islanded operation. Consequently, conventional control and protection approaches cannot adequately handle power transfer and various concurrent activities. The proportion of DG penetration in traditional utility networks is steadily rising [6]. In addition to the benefits offered by DGs, power system may also face serious unexpected situations during the isolation of the main utility grid as deposited in Fig.1 (island) due to regular electrical breakdowns or routine maintenance [7]. The most efficient ways to achieve technical coordination concerning the microgrid and the primary utility grid are determined amid careful inspection and analysis of islanding events [8]. Both planned, and unplanned islanding conditions are possible. Unplanned islanding can happen at any moment owing to systematic failures or other suspicions in the power system.

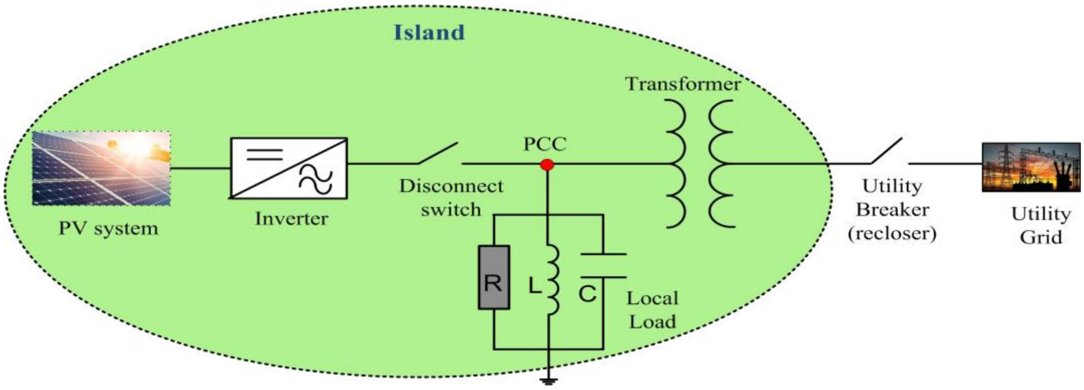

Fig. 1. Islanding formation in DG integrated-based power system

While planned islanding is part of the periodic maintenance needed for the primary utility [9]. The DG unit can operate either independently or grid interconnected. During grid-connected, a DG unit and the primary utility network deliver electricity to load centres in parallel, whereas, in the islanded state, the DG continues to supply power the residual load in case of a utility outage [10]. Unplanned islanding risks the electrical system's safety and might harm utility operations, endangering utility equipment and maintenance staff. The system's electrical components could be damaged, the resiliency of the power supply could be compromised, and the lives of maintenance workers could be in danger [11].

Table 1. International standards for IDM

Standard	QF	Detection time (ms)	Range of frequency	Voltage Range
IEC 62116	1	T < 2000	58.5 ≤ f 61.5	85% ≤ V ≤ 115%
Korean Standard	1	T < 500	59.3 Hz ≤ f ≤60.5	88% ≤ V ≤ 110%
IEEE929-2000	2.5	T < 2000	59.3 ≤ f ≤ 60.5 Hz	88% ≤ V ≤ 110%
UK G83/2	0.5	T < 500	47.5-51.5 Hz	87% ≤ V ≤ 110%
Canadian C22.2 No. 107-01	2	T < 2000	59.5-60.5 Hz	88% ≤ V ≤ 115%
French	2	Instantly	49.5-50.5 Hz	88% ≤ V ≤ 106%

Therefore, Islanding identification is a crucial problem and challenging issue in an electrical network adopting a hybrid power system. Voltage (V) and frequency (f) altitudes of DGs may be substantially impacted by unexpected power system islands that halt utility operations [12]. Thus, it raises a significant challenge for protection engineers and researchers using cutting-edge technology and power economics to solve these technical issues [13]. To ensure safe and dependable operation, islanding detection standards given in Table.1 offer guidelines and requirements for the design and operation of grid-connected systems.[14].

Different methods have been put out for power system islanding detection (ID). They are often classified into local and distant ID techniques [15], which is indicated in Fig.2. The local techniques are subdivided into passive IDM and active IDM. Passive approaches constantly observe system variables to identify islanding. Passive ID techniques include impedance [16], phase jump [17], rate of change of power [18] and rate of change of frequency (ROCOF) [19]. These techniques are easy to use and put into practice but a considerable non-detection zone (NDZ) exists. An area or loading state that might cause a detection technique to malfunction at the proper moment is called an NDZ. Due to their low cost and straightforward operation procedures, most power system enterprises use passive technologies. When a DG as an island has a considerable imbalance between the electrical load connected and the amount of power generated, these techniques work effectively. However, the passive method's effectiveness diminishes if the difference is small. Active techniques can detect changes in the system parameters by slightly perturbing the grid current.

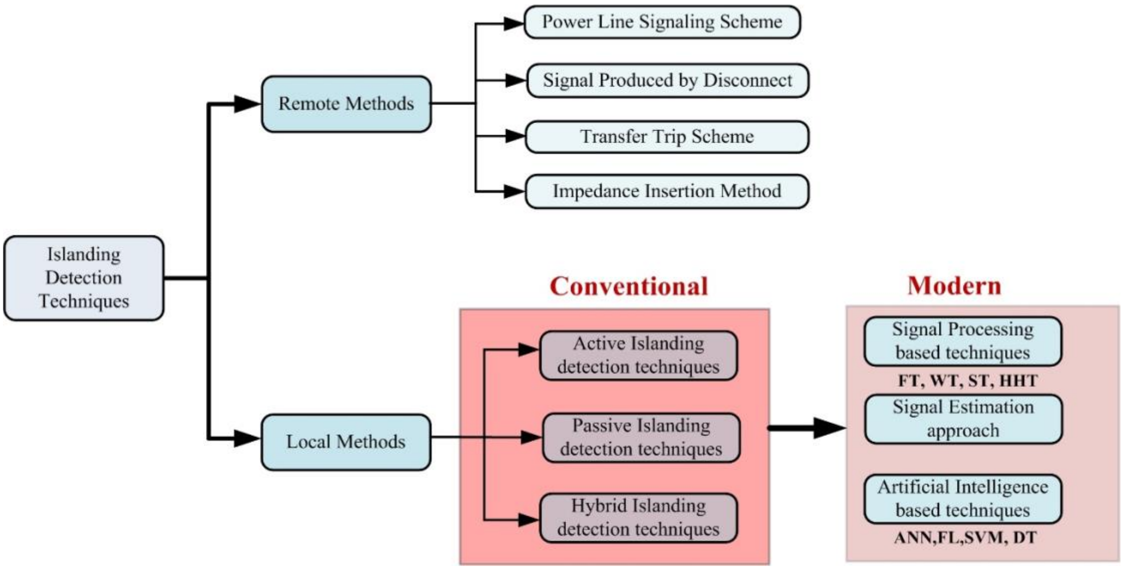

Fig. 2. Islanding detection techniques taxonomy

Active methods are slower than passive due to the system's intrinsic response time. Active techniques are inadequate as an ID criterion due to their influence on power quality and extraordinary expenses for execution. The slip mode frequency shift algorithms (SMFSA) [20], high frequency signal injection [21], negative sequence current or voltage injection [22], adaptive logic phase shift method [23], automatic phase shift algorithm, virtual capacitor [24], virtual inductor [25] are a few active islanding techniques. Despite having a low NDZ, some active approaches can lead to grid instability when used with multi-inverter-based DGs. Remote ID techniques use the utility and DG unit's communication channels. Due to their high implementation costs, these technologies are favourable for highly DG mixing but impracticable for DGs on a smaller scale. The transfer trip, impedance insertion, signal produced by disconnect are well-known ways to use the communication infrastructure to detect remote islanding [26].

Passive approaches are widely employed nowadays because of their appealing benefits. The dependability and precision of these approaches have increased due to the application of signal processing techniques in the time and frequency domains. As a result, these techniques are used in most current research in this area to shorten the NDZ. To identify islanding, harmonic content analysis of a power signal using an appropriate signal processing technique can be utilized to extract any fluctuation in the harmonic signatures. The methods that rely on the extraction of harmonics from voltage or current signals have been extensively studied in the literature and have been an advantageous way to identify islanding. Some digital signal processing (DSP) based approaches such as mathematical morphology (MMF) [27], Hilbert Huang transforms (HHT) [28] , time-time transform (TTT) [29], Stock well transform [30], Prony analysis [31] have offered satisfactory results within the shortest time for harmonics content extraction. Hardware difficulties and the incapacity to include different signals in a stationary Gaussian window are some of the approaches' drawbacks. Artificial neural networks [32], data mining [33], and fuzzy logic [34] are recent examples of intelligent approaches that have demonstrated effective performance even in noisy settings and with various load-generation characteristics [35]. These methods still involve a huge amount of statistics for training and rigorous training practices, resulting in a significant computational cost.

The Kalman filter (KF) based technique significantly benefits prior signal processing-based anti-islanding algorithms. It can detect the islanding state using the harmonic features scrutinized from the measured voltage at PCC. The suggested method also has a minimal non-detection zone (NDZ), which is robust against false operations. The KF is a useful filter for carrying out analyses in the time-frequency domain of voltage and current data. Because it produces the most accurate estimation of magnitudes with the fewest samples over the minimum time period. It performs effectively in a noisy environment and is lesser harmonically sensitive than the WT [36]. Therefore, the WT performance is always compromised when dealing with severely distorted signals and mother wavelet also influences the effectiveness of the WT. A KF, however, can precisely predict the intensity of a signal contaminated by noise with harmonics. KF is recognized as an optimum estimate technique that only needs a specific sample frequency value to be set and performed per the systematic design processes [37]. The suggested approach uses a KF as a harmonic analysis tool for the first time. Compared to other strategies, a KF-based strategy offers the following advantages:

Compared to previous time-frequency-based approaches, the latter is less susceptible to common disruptions such as extent noises. In actuality, it was designed for a loud atmosphere. The estimation of the next sample only requires two samples. Consequently, the procedure only requires a short period for initial decision-making. Also, a high sample rate could speed up the final decision process even faster. Implementation costs are minimal because only one voltage signal is used, and issues with current-based methods like current transformer saturation are also avoided. A KF is used throughout this research to wrest harmonic signatures from the voltage signal (MV) recorded. The harmonic features used as SHD, newly specified criteria for islanding detection, are then calculated using the collected contents. The proposed technique is confirmed by conducting several experiments during islanding and under normal circumstances. Additionally, the accuracy and computing cost of the proposed method's performance is much better than existing approaches. The following are the primary contributions of the proposed approach:

- Islanding identification using a time-frequency domain KF for harmonic signatures extraction.
- Measurements of the system's properties are used to make a KF formulation that works well.
- The term "SHD" is proposed for monitoring change detection as a specific criterion.
- Benchmark test cases are used to see how well the suggested method for detecting islanding works.

2. Proposed Islanding Detection Method

A suggested ID scheme involves monitoring the voltage at a single point where the DG unit connects to the power grid (PCC). The MV signal is generated from a three-phase voltage signal to enhance processing speed. The residual signal is derived, deducting the actual voltage signal from the estimated fundamentally connected component using a Kalman Filter (KF) with the desired speed. This residual signal is used as a criterion for detecting any event in the particular electrical system. Additionally, the KF extracts certain harmonic components to find an islanding condition. Based on these factors for detection, a new criterion is proposed. The definition of a novel scheme to differentiate the islanding condition from other regular situations considers harmonics based on different simulation results and literature works. Using a KF with the correct dynamic speed, the important odd harmonics, such as 3rd, 5th, and 7th, are extracted, and all exhibit significant indications in this regard, as demonstrated. Before constructing the residual signal, the voltage signal's estimated fundamental component is subtracted. If the KF's dynamic speed is well-tuned, the residual signal might reach a considerable level during the first few seconds following a change. However, it has no significant value under steady-state scenario, as the KF correctly monitors the modal signal eventually degrades. Any electrical system shift, including normal and island conditions, can be detected by comparing the residual signal to a predetermined threshold. The various processes are explained in more detail in the following subsections.

2.1. K-F Algorithm

The recursive processing of noise measurement data is essential to the Kalman filtering procedure. An optimal state algorithm called the Kalman Filter (KF) divides system parameters into samples using the proper gains. KF calculates electrical magnitudes based on sampled values in power systems. It is especially helpful when performing real-time digital signal processing and the input data is noisy or distorted. The desired error in the estimate, which may be the original error or the error in the input data, is utilized to compute the Kalman gain. This gain determines the relative significance of estimation errors versus input data. Kalman filtering necessitates a random variable as a starting estimate to compute the latest estimate. Similarly, the gain assigns a relative weight to the former estimate and the measured value to calculate the new estimate. A new estimation error is calculated built on the gain and the current estimate. This procedure is repeated until a revised estimate is obtained closer to the actual value. In power system applications, the KF is predominantly used for approximating voltage and frequency fluctuations. Kalman filter is also used to estimate voltage and current phasors dynamically. The suggested methodology employs the measurement-based Kalman Filter (KF) approach to estimate the harmonic components of a voltage signal measured at the output terminals of the Distributed Generation (DG) units. The Kalman Filter (KF) is a computational procedure that employs a series of mathematical equations and sequential data inputs to efficiently approximate the actual value of a signal or item under measurement in the presence of random variations in the measured values. The random process under consideration is represented by Eq. 1.

$$x_{k+1} = \varphi_k + x_k + w_k \qquad (1)$$

And the measurement process is expected to occur at some discrete points likewise the linear relationship at the time t_k as: Eq. 2.

$$z_k = H_k x_k + v_k \qquad (2)$$

Where, $x_k = (n \times 1)$ represents the process state vector, $\varphi_k = (n \times n)$ represents the transition state matrix $w_k = (n \times 1)$ represents the white sequence with known covariance matrix, $z_k = (m \times 1)$ is the vector measurement at time, t_k, $H_k = (m \times n)$ is the noiseless connection between x_k and z_k *at time* t_k and $v_k = (m \times 1)$ represents the measurement error which is sometimes supposed to be the white sequence.

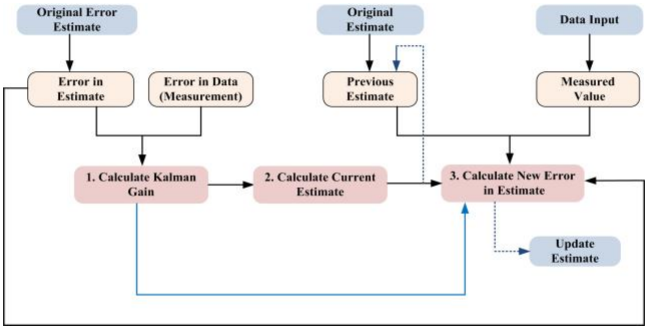

Fig. 3. Kalman Filtering Principle

2.2. Using KF to identify islanding

According to the KF, there is a recursive solution to the problem of linear discrete data filtering. One of two trend model-based or measurement-based—can be employed with a KF method. While measurement-based KF investigates the signal characteristics, model-based KF examines a power system model to linearize the system around its operating points. The suggested strategy takes advantage of the measurement-based KF methodology. In this instance, by adopting KF, the harmonic signatures from 3-phase voltage modulation at the DG output, which has already been translated into modal voltage, are determined. Assume that the modal signal given in Eq. (3) is received.

$$S_n = a\cos(\omega_o n + \varphi) \quad (3)$$

Where ω denotes the angular frequency, S_n is the nth sample of the observed modal voltage, and ϕ denotes noise. $\omega_o = 2\pi(f_o / f_s)$, f_s is the signal sampling frequency, f_0 is the system frequency, and fs is the signal sampling rate. The equation above may be transformed into a recursive equation for Sn by using a trigonometric deduction as Eq. (4).

$$S_{n+1} + S_{n-1} = 2\cos(\omega_o)S_n + \Psi_n \quad (4)$$

Where the n term is used for a zero mean arbitrary, it accounts for the modal signal's anticipated faults. These small variations in the amplitude and frequency of the MV may be among these mistakes. Zero means (*vn*) represents the MV signal as a representation of measurement noise and any relevant random noise, which is given in Eq. (5).

$$y_n = S_n + v_n \quad (5)$$

For the dynamical system model depicted in Eq. (3) the following linear state-space form must be defined:

$$X_{n+1} = Mx_n + b\psi_n \quad (6)$$

$$y_n = h^T x_n + v_n \quad (7)$$

Where,

$$X_n = \begin{bmatrix} S_n & S_{n-1} \end{bmatrix}^{-1}, b = \begin{bmatrix} 1 & 0 \end{bmatrix}^T,$$

$$M = \begin{bmatrix} 2\cos(\omega_0) & -1 \\ 1 & 0 \end{bmatrix}$$

The basic element of the modal voltage may be calculated using Eq. (6), (7). To acquire the other harmonics ω0 is changed to iω0 in the M is, where i exhibits harmonic order. As the amplitude and phase of the modal signal are absent from Eq. (6) and (7), the system's dynamic model is independent of these parameters. Therefore, ω0 and iω0 do not affect the KF's convergence.

Harmonics signatures of voltage signals that have been estimated by KF and utilized as inputs into well-known, s methods for identifying islanding in power systems. The sensitivity of the aforementioned quick approaches to harmonic signatures having a valid estimation for various operational situations can be corrected by a KF. A DG terminal voltage measurement's harmonic signature can be used to discriminate between islanding and grid-connected scenarios. At the outset of an islanding event, there is a sizable residual between the modal signal and its estimate. Utilizing the residual signal R_n is computed using Eq. 8.

$$R_n = S_n + y_n \quad (8)$$

Another criterion is established to distinguish between an islanding state and other modifications that are comparable to it. This criteria, known as SHD is computed using Eq. (10) and defined as follows.

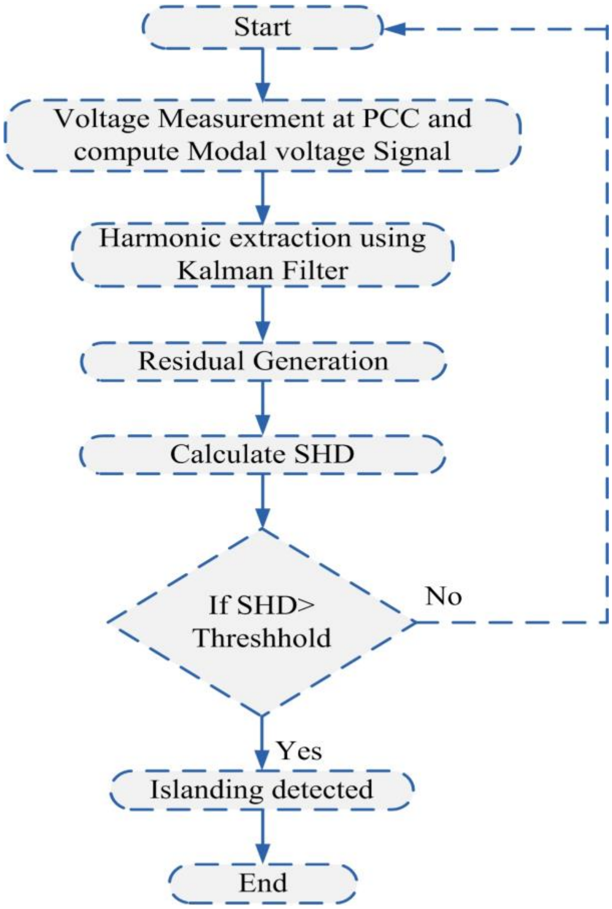

Fig. 4. Flow Chart Proposed Method

$$SHD = \frac{\sqrt{\Sigma_{n=3,5,7}^{\infty} V_{n\_rms}^2}}{V_1} \quad (10)$$

Where V_n is the RMS of the fundamental component, n is the order of the chosen harmonic. To detect islanding from other aberrant possibilities during a power supply fluctuation, the deviation of SHD is analysed concerning a preset threshold. Fig. 4 illustrates the sophisticated flow graph of the proposed ID approach. The flowchart depicts the measuring of a 3-phase voltage at the DG end terminal and its subsequent transformation into an MV signal. Once the MV has been measured, KF extracts the harmonic features. The KF code produces a residual signal that indicates the change happening in the system. The SHD signal's fluctuation distinguishes between islanding and typical operation circumstances.

2.3. Setting Threshold

An acceptable boundary for the suggested approach is calculated based Cubic spline interpolation (CSI) also names as Hermite spline. The CSI method records and analyses the threshold's lowest and highest variation points under various test situations [38]. The lowest and highest were adjusted to three for each test case circumstance. The peak magnitude of the SHD under normal situations peaked at three during the evaluation of the suggested strategy. Except for islanding, none of the cases under investigation went beyond this threshold. Therefore, it was assumed that the situation would be classified as islanding as soon as the threshold figure crossed the upper limit.

3. Simulation and Results Analysis

An integrated typical test system with several DERs is accessed to evaluate the suggested approach's performance. MATLAB simulation is adopted for numerous tests in typical and islanded working environments to examine and evaluate the suggested method's effectiveness.

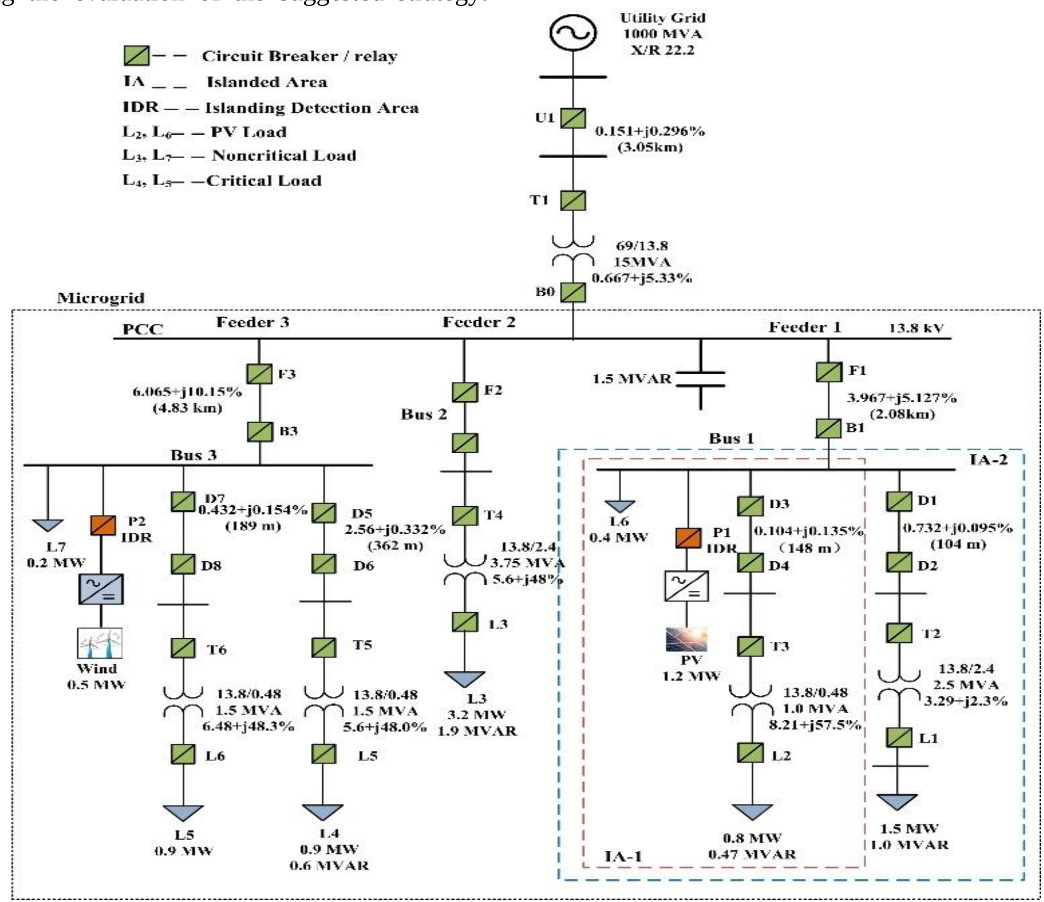

Fig. 5. Test System

3.1 System Testing

The suggested ID technique is assessed using a Matlab/Simulink model of a typical IEEE test system, shown in Fig.5, based on the IEEE 399 standard with certain changes. The testing system consists of a utility source at 69 kilovolts (kV), distribution feeders labelled F1, F2, and F3, a short-circuit power of 1000e3 kVA, and an X/R ratio of 22.2. There is a collective bank of 1.5 MVAR fixed shunt capacitors has been placed on F1 and F3 of the substation. The 0.5 Megawatts (MW) wind DG, and the 1.2 Megawatts (MW) PV DG are also secondary components of the test system. Radial feeders are required to deliver power to seven (L1-L7), including a diode rectifier and resistive and inductive (RL) branches. For more on the testing environment, please refer to [36]. The Islanding Detection Test in Fig.5 depicts two islanded locations (I-A and I-B). When CB-F1 is on, it indicates that the microgrid is running with a balanced load or I-A. CB-D1 must be opened to release load L1 for the simulation to run smoothly. When CB-F3 is opened, I-B represents a different microgrid with parallel RLC load conditions (resistance, inductance, and capacitance). As a simulation, we let L4's burden go by opening CB-D5. Testing equipment used voltage meters to check P1 and P2 islanding-detection relays.

3.2 Non-Islanding Tests

By modeling a few non-islanding occurrences, the capacity of the suggested technique is evaluated under typical operating settings. Several other conditions share the islanding condition's signature, and this condition develops as a result of various adjustments to the system's characteristics. These adjustments could involve starting a motor, switching a capacitor, starting a strong load, or changing the load. Numerous tests are carried out to prevent malfunction of the suggested strategy. For convenience and compacting the paper, only the simulation results from a situation with a quick change in load in both DG units are given.

a. Changes in PV DG Load Suddenly:

The suggested method was tested under several non-islanding situations, which occasionally exhibit islanding-like characteristics. An abrupt change load event was taken into account for a PV based DG to test the robustness. Bus 1 is connected to a three-phase dynamic load that may mimic a sudden increase in demand. The load block's step time was set to t = 0.5s. The positive sequence voltage affects the active power P and reactive power Q in a dynamic load model. It was decided to change the P and Q of the load model from 12 MW to 8 MVAR, respectively. The results shown in Fig.6 show that the suggested method does not fail when the load changes quickly.

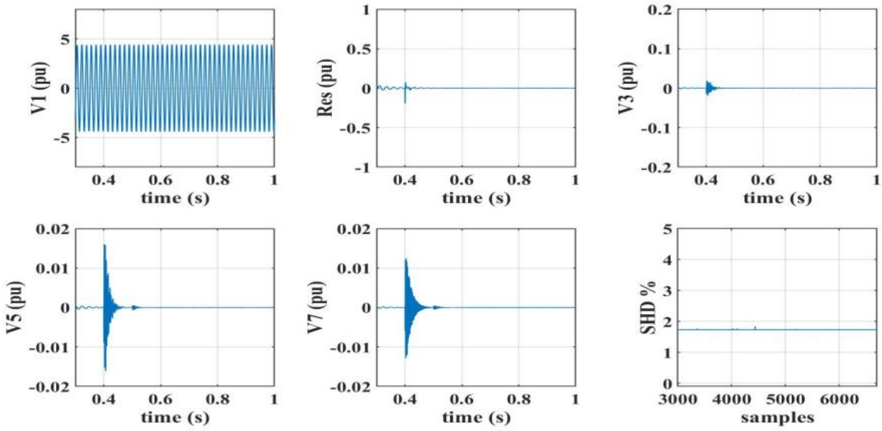

Fig. 6. Sudden load fluctuation in PV DG

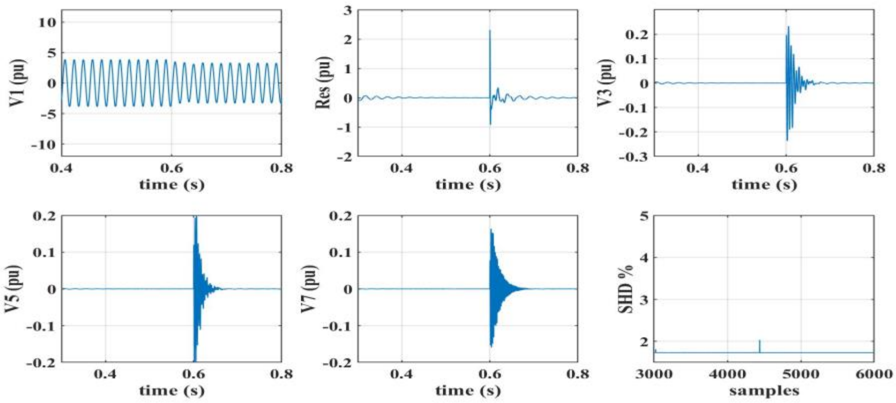

Fig. 7. Sudden load fluctuation in Wind DG

b. Sudden load change in wind DG:

A sudden load shift is also taken into account for the wind DG unit when a significant inductive load is introduced to the network at time t = 0.5 S. The system characteristics are significantly altered as soon as reactive power is connected. Identical waveform characteristics of voltage or current might be produced by such a shift, which could lead to the islanding measures failing. It can be shown from the findings in Fig.7 that the suggested approach does not malfunction when the load changes. This finding attests to the suggested technique's accuracy in no islanding occurrences.

3.3 Islanding Tests

To evaluate the efficacy of the proposed IDM, many islanding scenarios are recreated in a conventional test system. The parallel RLC load and matching load circumstances are the three significant islanding situations taken into consideration here. Due to their limited NDZ, these two circumstances are regarded as challenging for passive approaches to detect the islanding state. The suggested method successfully and quickly picks up these islanding circumstances.

a. Islanding detection with a parallel RLC load:

This is a typical procedure for verifying the efficacy of passive island detection methods. An isolating scenario was simulated to test the proposed approach. Buses 1 and 3 were linked in parallel to a constant-impedance RLC load when CB-B1 and CB-B3 were tripped at t = 0.5s, creating an islanding condition. Fig.8 depicts the results, which show how reliably the islanding condition can be diagnosed. The proposed method may detect PV and wind DG islanding at the time of occurrence (t = 0.5s). Results show that both DG units complete their islanding detection procedures in a single power frequency cycle. This demonstrates how quickly and accurately the KF technique may detect an islanding process.

b. Islanding detection in an imbalanced condition

An islanding identification was conducted under an unbalanced load scenario to analyze the effectiveness of the suggested approach. At time t = 0.5 seconds, the islanding situation is established by activating CB-F3. Fig.9 shows the findings that were attained. The islanding was created at time t = 0.5 and is discovered at time t = 1.05 seconds as indicated in the findings (50 milliseconds detection time). The speed with which the worst-case scenario was found illustrates the effectiveness of the proposed technique.

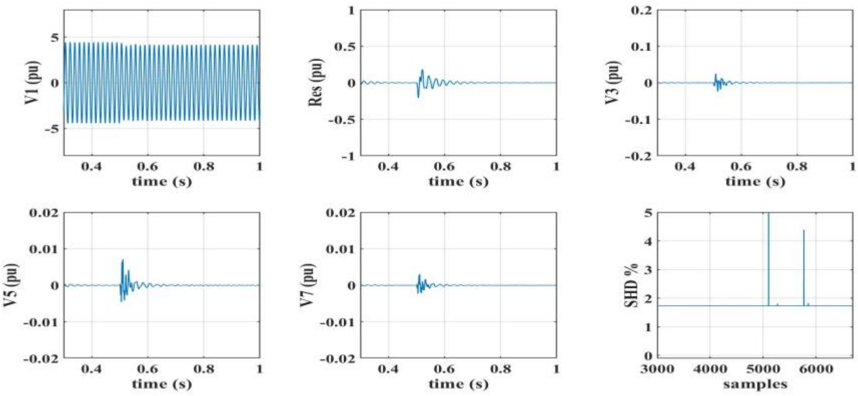

Fig. 8. Islanding detection with a parallel RLC load PV

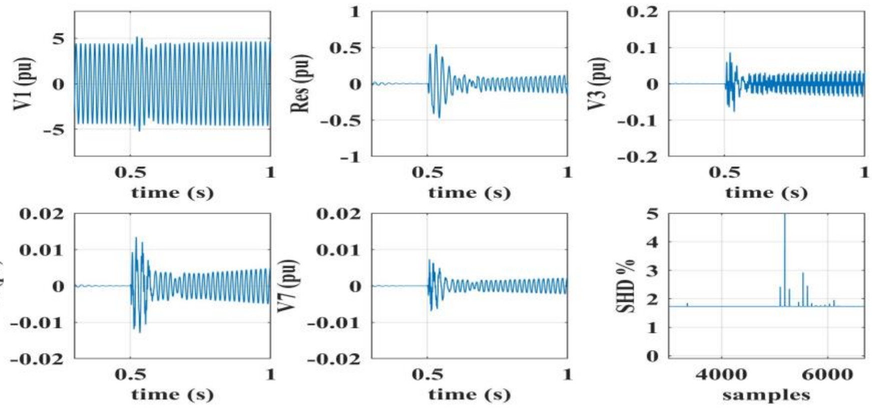

Fig. 9. Islanding detection in an imbalanced condition

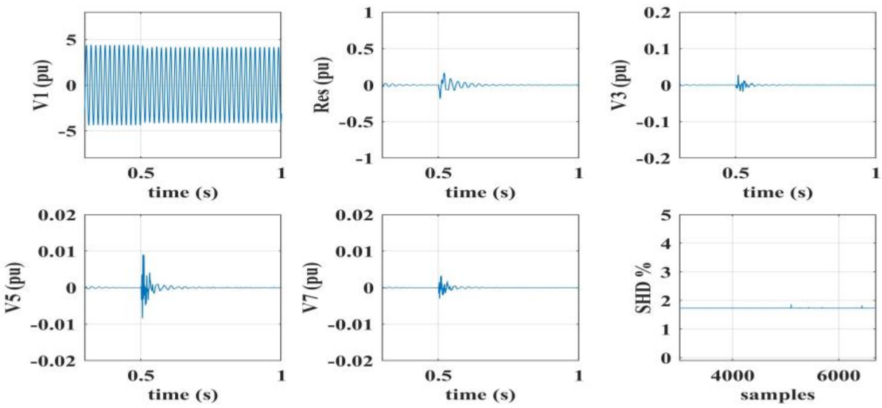

Fig. 10. Islanding detection in balanced condition

c. Islanding detection with balanced load-generation

A simulation test case for islanding detection was performed using a load generation matching scenario called as balanced load generation to evaluate the performance of the proposed ID. For this evaluation, we modified the load resistance value to apply an active power equivalent to the production of the PV DG system. The islanding is created by activating CB-F1 at t = 0.5 seconds. In Fig.10, the findings that were obtained are shown. The islanding occurs at time t = 0.5 and is discovered at time t = 5.07, as indicated in the findings (70 milliseconds detection time). This validates how quickly and effectively the KF method detects an islanding condition.

3. Discussion

Nowadays distribution generation sources such as solar based, wind turbines, or micro hydro based generators offers numerous benefits, including reduced transmission losses, enhanced grid resilience, and the potential for increased energy efficiency [39]. Moreover, with the increasing integration of renewable energy sources and distributed generation, accurate islanding detection becomes even more crucial to effectively manage and control complex power system configurations [40]. Unintentional islanding situations can lead to safety hazards for utility workers attempting to restore power and can damage sensitive equipment when power is suddenly restored. By promptly islanding detection lies in its critical role in ensuring the safe and reliable operation of power systems. A robust passive intelligent demand management (IDM) system is introduced, that includes a feature extraction approach from PCC voltage using Kalman Filter (KF). The procedure is modest and economical for practical application because large data computations are not required for training and testing, as is the case with other modern techniques. Extensive simulations have been conducted for the islanding and normal conditions that includes different active as well as reactive power imbalances and load variations. Based on results assessment, it is shown that the suggested technique has an insignificant NDZ, which was verified using the IEEE Standard test system.

4. Conclusion

The proposed KF-based approach is a reliable and adaptable method for islanding detection in various settings. Its statistically optimal ability to combine measurements and predictions enables accurate detection of islanding events, ensuring the safety and stability of power systems. By taking into account variables such as modal voltage, and system dynamics, the Kalman filter can identify islanding conditions while minimizing false alarms. The method is simple and economical because only a single variable is measured and tracked; the current signal doesn't need to be monitored. Extensive simulations following IEEE 1547 islanding testing circuit were done, considering both small and large power imbalances and the disconnection of a large portion of the load for both islanding and non-islanding occurrences. It has been demonstrated that the KF-based method accurately and speedily detects islanding conditions. The key advantages of the method are that it is quick, precise, and performs well in noisy real-world circumstances because of the specified criteria based on a KF. Furthermore, it is a reliable solution for islanding detection across various instances due to its adaptability to various system setups and the potential for integration with other cutting-edge algorithms.

Integrating machine learning methods like artificial neural networks or support vector machines with the Kalman filter could be a promising direction for future study. By learning from large amounts of data and patterns, these methods can help to improve detection methods.

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