Comparative Analysis of Different Signal Processing Schemes for Islanding Detection in Microgrid

Prajna Parimita Mishra, Chandrashekhar Narayan Bhende, and Akshaya Kumar Pati

Abstract In this paper, islanding detection in a microgrid scenario is analyzed by using the signal processing techniques such as the S-transform method (ST), Sparse S-transform (SST), variational mode decomposition method (VMD) and total variation filtering method (TVF). To get a clear picture of the comparison, all the detection schemes are evaluated in the standard 13-bus distribution system. In this paper, the PCC voltage of a three-phase system is utilized for further signal processing and subsequent feature selection procedure. The extracted voltage is also called as modal voltage. Various monitoring parameters have been considered to check the effectiveness of the selected threshold and subsequent islanding detection. Further, the detailed overview of above-mentioned methods has been thoroughly discussed.

Keywords Distributed generations (DGs) · Islanding detection · Signal processing schemes · Modal voltage signal

1 Introduction

In recent decades, the eco-friendly nature of renewable source leads to increase uses distributed generation systems (DGs) in the power system network. Mostly the photovoltaic and wind turbine system are widely used as renewable energy sources. The integration of renewable sources with the grid arises several issues. In general, the islanding condition arises when one or more DGs continue to energize the loads even though the power from the utility is under a cutoff state. If such island conditions are not identified at right time, it may cause serious harm to the equipment and working personnel. So it needs an accurate and timely detection of the islanding

P. P. Mishra (✉)
School of Electrical Engineering, KIIT Deemed to be University, Bhubaneswar, India
e-mail: prajnaelect@gmail.com

C. N. Bhende
School of Electrical Sciences, IIT Bhubaneswar, Bhubaneswar, Odisha, India

A. K. Pati
School of Electronics Engineering, KIIT Deemed to be University, Bhubaneswar, India

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states. According to the IEEE 1547-2003 standard, the islanding must be detected within 2 s [1].

Generally, the islanding detection approaches are categorized as active, passive, and communication-based techniques. Among the methods, the passive islanding method of detection requires monitoring of the system parameters such as voltage, frequency, and total harmonic distortion of the signal. It is also convenient for implementation, however, the major disadvantage of this technique is the large non-detection zone (NDZ) which depends on the accurate selection of the threshold value. Some of the commonly used passive methods are: Over/Under voltage protection (OVP/UVP), rate of change of voltage (ROCOV), rate of change of power (ROCOP), Over/Under frequency protection (OFP/UFP), and rate of change of frequency (ROCOF), etc. [2]. The active method is based on monitoring the system's response by injecting an intentional disturbance. In this method, the NDZ is negligible in width, but due to the injection of the external disturbance, power quality deteriorates [3]. Some other active methods such as Sandia frequency shift, slip-mode frequency shift, and active frequency drift are also reported in the literature [4]. The drawbacks of both active and passive methods are overcome by the communication method. In this method, direct communication between the utility and DG exists [5]. But, practical implementation of this method costs more. Another method called the hybrid approach which is the combination of both active and passive islanding methods, is reported in the literature [6, 7]. But, it increases the overall complexity of the system. From the above-mentioned overview, as compared to other existing methods, the passive techniques have more advantages in terms of cost-effectiveness, detection speed, and also it doesn't have any impact on power quality. Therefore, the passive detection scheme equipped with an effective NDZ reduction feature is a promising solution to the islanding detection problem.

Further, various signal process tools are applied to the test signal to overcome the drawbacks of the passive method, i.e. large NDZ issues. In an islanding detection method, extracting the hidden characteristics of the signal plays an important role in the accurate detection of the islanding. This can be done by using powerful weapons like different signal processing techniques which are very much versatile, stable, and also cost-effective. Some of the important signal processing tools are Fast Fourier transform (FFT), TT-transform, Kalman filtering, Hilbert Huang transform, Wavelet transform (WT), S-transform, etc. [8]. Further, some other signal processing methods such as wavelet packet transform and backpropagation neural network for island detection are presented in [9]. Another study that uses the artificial neural network and its synchronized phasor data for islanding detection is described in [10]. In this study, the signal processing schemes such as the S-transform method (ST), Sparse S-transform (SST), Variational Mode Decomposition method (VMD) and total variation filtering method (TVF) are used for islanding detection. The effectiveness of these detection schemes has been discussed.

This paper is organized as follows. The description of the system considered for the proposed comparative analysis is discussed in Sect. 2. The details of these signal processing schemes have been discussed in Sect. 3. Section 4 shows the comparative results of the studied observation along with the complete overview of the methods. The overall conclusion is presented in Sect. 5.

2 Test System Configuration

This section presents a detailed description of the system considered for the proposed study of the effectiveness of various signal processing-based islanding detection schemes. In this study, a standard test system of photovoltaic system integrated into a standard IEEE 13-bus distribution network is considered as shown in Fig. 1. The test system contains a substation, 13 numbers of nodes or buses with 11 line sections and many loads. Different types of loads such as balanced, unbalanced, nonlinear and dynamic loads are considered. The substation rating is taken as 115 kV, further, it stepped down to a level of 4.16 kV by using a distribution transformer. The PV system of 14,1 kW rating is connected to the network. The PV system is integrated into the bus through an inverter and transformer, the transformer T2 is used to step

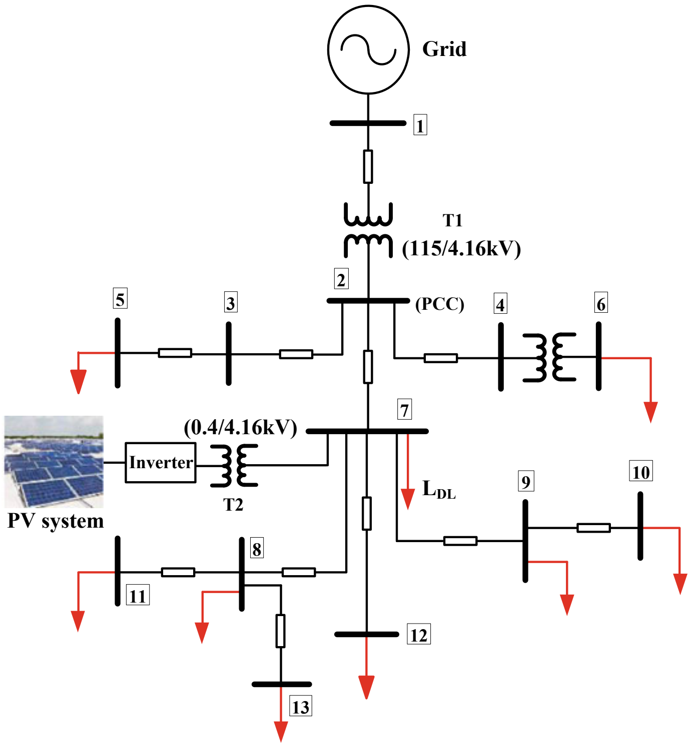

Fig. 1 Grid interactive 13-bus distribution network for islanding detection

Table 1 PV system parameters

Parameter	Value
Short circuit current (I_{SC})	8.01A
Open circuit voltage (V_{OC})	36.90 V
Number of series connected PV module	22
Power rating of the series connected PV array	4.7 kW
Number of such series connected PV array	3
Maximum power rating of the PV array	14.1 kW

down the voltage to 400 V. The parameters of data of the IEEE 13-bus system are taken from [11] and the PV system parameter is given in Table 1.

The voltage at PCC (as shown in the Fig. 1) of the three-phase system is measured, and then, by applying a linear combination of the three-phase voltages, the modal voltage signal is obtained. This parameter is used as the test signal for the detection schemes.

3 Signal Processing-Based Islanding Detection Schemes

The contribution of various signal processing techniques for efficient passive islanding detection is well documented in the literature. The NDZ is a significant parameter of the passive islanding detection method. Due to the advancement of signal processing tools (as the method reported in recent literature) [12–19], which have been applied to the passive islanding method to reduce the NDZ. Many such widely accepted advanced tools for signal decomposition are: wavelet singular entropy [12], data mining [14], Bayesian classification [15], pattern recognition [13], artificial neural network [16] and S-Transform (ST) [17]. The advantages, as well as shortcomings of these methods, are outlined in [18]. In this paper, the detection scheme based on S-transform, Sparse S-transform (SST), Variational Mode Decomposition method (VMD) and Total Variation Filtering method (TVF) are discussed. The details of these signal processing schemes are given in references [17, 19, 20] and [18], respectively (Fig. 2).

In the islanding detection scheme based on signal processing techniques, the first step is considered as extraction of three-phase voltage signal from the PCC of the system. In the second step, to get the corresponding modal voltage, the PCC voltage signal is computed through the modal voltage transformation. In the third step, the obtained modal voltage signal is passed through the processing algorithms for further signal processing. To characterize the decomposition, suitable features are extracted from the decomposed signal. To evaluate the behaviour of the signal, it is further monitored by comparing it with pre-specified threshold values. The threshold value for the islanding detection techniques is calculated by considering the signal behaviour under various network disturbances conditions. The logic behind

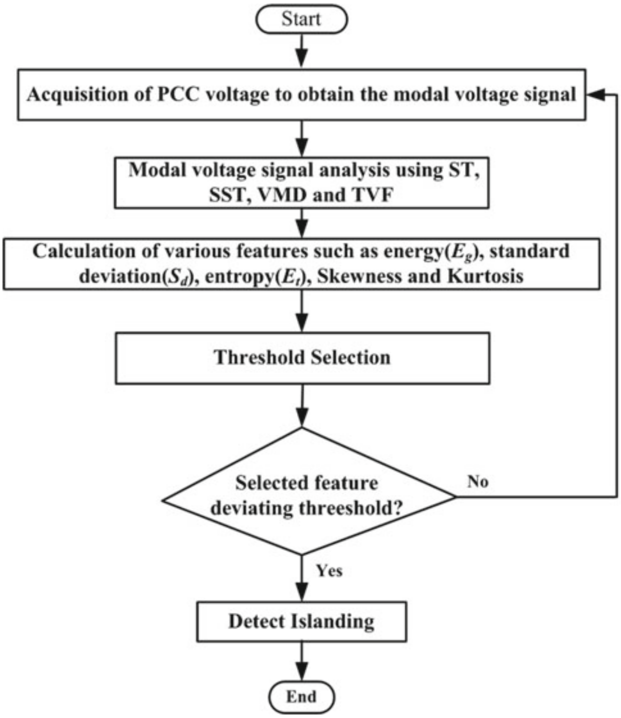

Fig. 2 Flowchart of the signal processing based islanding detection method

the selection of threshold is that the islanding condition should be accurately identified and the other normally occurring non-islanding events should be ignored by the island detection method. While calculating the threshold, the following disturbances are considered such as grid's X/R ratio variation between the range of 5 to 15, grid frequency variation between 49.5 Hz to 50.2 Hz, power quality disturbances, i.e. variation in swell/sag conditions, zero power mismatch between distributed generation and the load and increase of *R-L* load value by 50%,

4 Results and Discussion

All the schemes discussed above detect the islanding condition very effectively. However, in order to get a comparative analysis of different decomposition schemes, various performance measures are considered. To evaluate the effectiveness of various islanding detection techniques, various criteria such as the detection time taken by the schemes, the minimum number of statistical parameters required for accurate detection and the effectiveness of the selected threshold are considered. To get a clear picture of the comparison among the signal decomposition methods, all the schemes are evaluated on the same system of Fig. 1 with the introduction of 20 dB noise into the PCC voltage. This performance of the system is analyzed on the computer processor of Intel i3 with 2.8 GHz, 8 GB RAM computer and in MATLAB/SIMULINK platform. The input voltage signal to the algorithm in case of all the detection schemes contains three cycles of data (600 samples).

4.1 Detection Time

The accuracy of the islanding detection time is of prime importance. As per the IEEE Std. 929-2000, the DG should be disconnected after detection of islanding. Similarly as per the IEEE Std. 1547-2003, the islanding condition should be identified within 2 s of its formation. However, in case of power system protection, the detection should be always faster so that decision-making for further remedial action can be better. In this section, in order to get a comparative analysis of different decomposition schemes, the islanding detection time is treated as an important parameter. The islanding detection time consists of the algorithm time (time taken by the algorithm) and the execution time (time interval between the receiving of the input signal and the generating of the trip signal). The details of the time taken by various decomposition methods are presented in Table 2.

As noticed in Table 2, all the decomposition methods are able to achieve fast detection. However, among the schemes, TVF-based detection scheme is the fastest to detect islanding in a noisy environment.

Table 2 Comparative analysis of different signal decomposition based islanding detection algorithms in a noisy environment

Events		Algorithm time (ms)	Islanding detection time/execution time (ms)
S-Transform [69]		15.32	32
SST with	Automatic Scaling	7.3	26
	Harmonic Scaling	6.49	23
	Dyadic Scaling	4.67	21
Variational mode decomposition (VMD) based scheme		3.357	17
Total variation (TV) based filtering scheme		2.562	16

4.2 Number of Statistical Parameters

In case of passive islanding detection algorithms, the selection of powerful monitoring parameters plays an important role in successful islanding detection. For the analysis of signals, various statistical parameters were used. The statistical parameters such as energy, standard deviation (SD), variance, energy, entropy, kurtosis and skewness are used in signal decomposition-based algorithms. In case of TVF-based detection approach, along with the statistical parameters, the rate of change of positive sequence phase angle (ROCOPSA) is also considered in order to enhance the reliability of the islanding detection scheme. In many of the detection schemes, reported in the literature, these statistical parameters are efficient in detecting the disturbances. But, for the accurate islanding detection, those parameters that demonstrate maximum changes to the disturbance are considered more suitable. So in this context, the most suitable and efficient parameters are selected for the proposed detection schemes for the successful islanding detection. Then the parameters are compared with the pre-defined threshold value. If the value of the parameter deviates from the pre-specified threshold value, then the islanding detection method will generate a trip signal to the corresponding relay for the isolation purpose. The number of parameters required for the proposed detection schemes are given in Table 3.

As observed from Table 3, SST-based scheme required three statistical parameters, whereas the VMD and TVF-based schemes can detect islanding accurately with two numbers of statistical parameters.

Table 3 Comparative analysis of different islanding detection algorithms in terms of statistical parameters

Detection scheme	No. of statistical parameters required
Sparse S-Transform (SST)	3
Variational mode decomposition (VMD)	2
Total variation filtering (TVF)	2

Table 4 Comparative analysis of different islanding detection algorithms in terms of their effectiveness in threshold selection

	Threshold	Value of parameters for islanding with load $Q_f = 2$	Percentage difference (%)
SST (Dyadic Scaling)	Energy > 150	212.87	29.53
VMD	Kurtosis < 7	3.6339	48.08
TVF	ROCOPSA > 7	18	61.11

Table 5 Overall comparative analysis of different signal processing algorithms

Description	S-Transform	SST	VMD	TVF
Property	A variable and scalable localizing Gaussian window is used while decomposing the signal	Advanced version of S-transform in which sparsity can be incorporated	Signal is decomposed into a group of band limited IMFs (intrinsic mode functions)	Effective algorithm for signal decomposition under noisy environment, whose derivation is based on minimax property
Distinct feature	Provide frequency dependant resolution	Introduction of sparsity	Signal separation is accurate and robust to noise	Effective enough while preserving the sharp edges of the given signals during noise removal
Technique	Time–frequency resolution	Time–frequency Resolution	Analysis of signal is an adaptive and non-recursive method	The objective function is described in terms of a Convex optimization problem
Methodology	Feature extraction and then detection	Feature extraction and then detection	Feature extraction and then detection	Feature extraction and then detection
Islanding Detection	Yes	Yes	Yes	Yes
NDZ	Low, since detection is degraded to some extent under harmonic condition [21]	Negligible	Negligible	Negligible
Advantage	Dilation and translation of localizing scalable Gaussian window with absolute phase spectrum	Less memory requirement, Fast computation	Faster as compared to SST	Faster as compared to VMD
Disadvantage	Calculation requirement and computational burden are quite high	Possibility of selected frequency band may not be always having vital information	VMD requires the number of modes to be pre-defined. Convergence is sensitive to noise	Proper selection of Regularization parameter (λ) is highly essential in order to retain vital signal information

(continued)

Table 5 (continued)

Description	S-Transform	SST	VMD	TVF
Efficiency	Low	High	High	High
Reliability	Yes	Yes	Yes	Yes
Scope for improvement	Possible through other variants of S-transform such as SST	More analysis to select the relevant frequency band for sparsity	Criteria for automatic determination of the number of modes	Automatic selection of λ

4.3 Effectiveness of Selected Threshold

In case of passive islanding detection schemes, proper threshold selection plays a crucial role in the success of the detection scheme. Therefore, there is a necessity to have a comparative study of the effectiveness of the selected threshold for different algorithms. Thus, to compare the effectiveness of various islanding detection algorithms, the percentage difference between the specified threshold value and the monitoring parameter value is considered. In order to get the comparison, the critical case of islanding with a load having a quality factor equal to 2 is taken into account for all the three algorithms. For each algorithm, the percentage difference between the specified threshold and the monitoring parameter value during the high load quality factor event is presented in Table 4.

As observed from the above table, all the proposed passive islanding detection schemes are efficient enough to detect the critical case of islanding along with accurate threshold selection. However, among all the algorithms, the percentage difference between the algorithm's threshold and the corresponding monitoring parameter value is large in case of TVF as compared to other algorithms. Apart from all the above analyses, a complete analysis of different signal processing techniques used in this work is presented in Table 5. From the above analysis, it is observed that the TVF-based detection scheme is the most effective one among the other specified algorithms.

5 Conclusion

This paper has presented a comparative analysis of a plethora of signal processing-based islanding detection techniques which include S-transform (ST), Sparse S-transform (SST), Variational Mode Decomposition (VMD) and Total Variation Filtering (TVF). In order to compare the effectiveness of these algorithms, various monitoring parameters such as detection time, number of statistical parameters required and effectiveness of threshold are evaluated in the studied system. The test system includes a standard IEEE 13-bus distribution system with the introduction of noise. From the analysis, it is concluded that in a noisy environment, although all signal decomposition schemes are effective for successful islanding detection, the TVF-based decomposition scheme outperforms other schemes in successful islanding detection. This analysis will help the power engineer to choose the most effective tool for effective islanding detection in a microgrid scenario.

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