IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

Received 30 June 2022, accepted 11 July 2022, date of publication 20 July 2022, date of current version 25 July 2022.

Digital Object Identifier 10.1109/ACCESS.2022.3192554

SURVEY

A Comprehensive Survey on Islanding Detection Methods of Synchronous Generator-Based Microgrids: Issues, Solutions and Future Works

REZA BEKHRADIAN AND MAJID SANAYE-PASAND, (Senior Member, IEEE)
School of Electrical and Computer Engineering, College of Engineering, University of Tehran, Tehran 14395-515, Iran

Corresponding author: Majid Sanaye-Pasand (msanaye@ut.ac.ir)

ABSTRACT Nowadays, the penetration of distributed generations (DGs) and microgrids (MGs) has been significantly increased due to the technical, social, environmental, and financial reasons. One of the most common types of DGs which is widely used in different networks is small-scale synchronous generators (SSSGs). Synchronous-based microgrids (SGBMGs) and SSSGs can operate under both grid-connected and islanded conditions. To guarantee a stable, uninterruptible, and safe autonomous operation, the unintentional islanding events should be quickly detected and then, appropriate control and precaution actions should be performed. Various islanding detection techniques have been proposed in the two past decades including remote and local methods. Meanwhile, local methods can be divided into two major groups, i.e. passive and active methods. To select the most suitable islanding detection scheme (IDS), various factors including the DG type and its technology should be considered. Therefore, the IDS for SGBMGs may be completely different from that for inverter-based microgrids. In this paper, the suitable IDS which can be practically applied to the SGBMGs are comprehensively investigated. To do so, at first, various suitable indices are introduced which can be properly employed by the system engineers and researchers to compare various IDS and select the most appropriate one. Then, various types of existing IDS are carefully investigated using these indices. Based on these investigations, it is concluded that local passive methods are more appropriate for SGBMGs due to their technical and economic benefits. Moreover, to enhance the existing IDS, some ideas are provided in this paper which can be considered in the future research works.

INDEX TERMS Small-scale synchronous generator (SSSG), synchronous generator-based microgrid (SGBMG), islanding, islanding detection.

I. INTRODUCTION

Recently, the penetration of microgrids (MGs) containing distributed generations (DGs) and local loads has been increased due to various motives including improvement of power supply reliability and resiliency, reduction of power outage period, preventing momentary interruption of essential loads, reduction of environmental concerns including greenhouse gases, providing a cost-effective power supply for mining digital currencies and some other economic incentives [1]–[3]. Various DGs technologies based on renewable or non-renewable energies can be employed for integrating the MGs [4], [5]. The suitable technology of the DG is generally determined based on different factors including economic feasibility studies, required reliability, and technical requirements of grid code including fault-ride-through capability [5], [6].

One of the most common types of DGs which is widely used along with both renewable and non-renewable energies is small-scale synchronous generators (SSSGs) which can provide smooth and high-reliable power required for the essential loads under both grid-connected and islanding conditions. During the grid-connected operation, the excessive power of synchronous-generator based microgrid (SGBMG) can be sold to the energies markets [7]. However, grid-connected SGBMG may have some adverse impacts on

The associate editor coordinating the review of this manuscript and approving it for publication was Nagesh Prabhu.

the distribution system especially its operation and protection [1], [2]. Therefore, various precaution actions should be performed to eliminate these unfavorable effects. After disconnection of the SGBMG from the upstream distribution grid, the islanded controlling system should be activated automatically to preserve the SSSGs stability [8]. Therefore, the islanding condition of SGBMG should be quickly detected to avoid power interruption of local essential loads and prevent adverse effects on the upstream grid. Islanding or loss of main can be defined as a condition in which the MGs or DGs are disconnected from the main grid [9]. This isolation may take place in one phase or multiple phases due to various events including planned or unplanned trips of upstream circuit breakers, fuse failures, broken conductors, and short circuit faults. These events may occur at the upstream distribution system or the MG. Islanding events may occur intentionally (scheduled) or unintentionally (unscheduled) [10]. The unintentional islanding situations should be detected quickly to perform proper actions for retaining the secure operation of the system.

Various islanding detection schemes (IDSs) have been proposed by researchers and commercial industrial companies in the past two decades. To select the most suitable IDS, the power system engineers should consider various factors including the DG type and its technology (i.e. synchronous generator-based or inverter-based MGs), grid codes, required standards specifications, and control/protection system requirements. To satisfy these requirements many methods have been proposed which can be divided into local and remote methods [11]. To adopt the most appropriate IDS for a specific SGBMG, some major factors should be considered by the system engineers including simplicity, straightforward and low-cost implementation, security, and dependability.

The dynamic behavior of SGBMGs and other types of microgrids especially inverter-based microgrids (IBMGs) are different after islanding occurrence. The frequency of SGBMG changes after islanding events even for small amounts of power mismatch due to the mechanical inertia of SSSGs. Consequently, the SGBMG frequency would reach to the frequency relays thresholds. In fact, the SSSG frequency exits the permissible range after a while and SSSG becomes unstable without inserting any intentional disturbance. In such a condition, the rate of change of frequency depends on the SSSG inertia. However, for the inverter-based microgrids (IBMGs), the frequency may not change significantly after a long duration, and to detect islanding condition an intentional disturbance may be required [12], [13]. This perturbation is mainly employed to create an intentional power mismatch which leads to voltage and frequency drifts from their nominal values. Based on these explanations, active methods are commonly adopted by IBMGs while these methods are not recommended for SGBMGs [14]. Therefore, the appropriate IDS should be employed depending on the type of microgrid.

In this paper, various methods for islanding detection of SGBMGs have been outlined. To do so, the proper indices for evaluating the performance of IDSs are presented at first. These indices help power system engineers to select the most suitable IDS for a specific SGBMG. Then, various types of IDSs applicable to SGBMGs are carefully investigated and compared using the discussed indices.

II. APPROPRIATE PERFORMANCE EVALUATION INDICES FOR SGBMGs

To evaluate and quantify the effectiveness of islanding detection methods, suitable indices and techniques should be utilized. To do so, various methods and criteria are recently proposed by different articles and standards. For instance, the technical requirements for the secure operation of MGs (such as required detection time) which are given by various standards are presented in Table 1. As shown in this table, only IEEE 1547 is applicable to SGBMGs. In this section, some suitable evaluation indices for SGBMGs and their calculation procedures are expressed in detail.

TABLE 1. International standards for islanding detection.

Standard	MG type	Load quality factor	Frequency range (Hz)	Voltage range (pu)	Required detection time
IEEE 1547	All types	1	59.3 – 60	0.88 – 1.1	< 2 s
IEEE 929	PV	2.5	59.3 – 60.5	0.88 – 1.1	< 2 s
IEC 62116	PV	1	59.3 – 60	0.88 – 1.15	< 2 s
German VDE 0126-1-1	IBMG	2	47.5 – 50.2	0.88 – 1.15	< 0.2 s
Canadian C22.2 No. 107-1	IBMG	2.5	59.5 – 60.5	0.88 – 1.06	< 2 s

A. NON-DETECTION ZONE

Non-detection zone (NDZ) is the most widely-used graphical tool to evaluate the performance of the islanding detection relays [15]–[17]. This region presents the amount of active and reactive power mismatches where the IDS fails to detect the islanding condition within the permissible time [18], [19]. In addition, NDZ should be extracted to adjust the relay thresholds, especially for conventional techniques [15]–[20].

To determine the NDZ boundary, both electromagnetic simulation-based studies and analytical-based techniques can be employed [17], [20]. It should be noted that the NDZ extraction concept of SGBMGs is different from that of IBMGs [20]. Since IBMGs have no mechanical inertia, their NDZ region is mainly influenced by the RLC load quality factor and resonant frequency [20] and the detection time is less important for their NDZ extraction. On the other hand, the

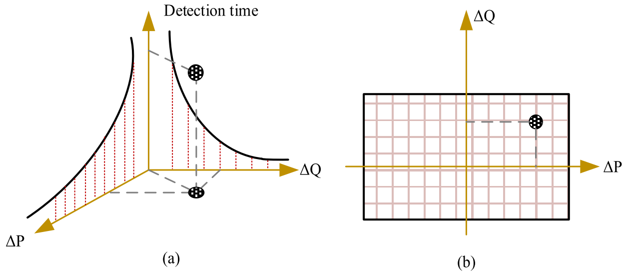


FIGURE 1. **(a) Islanding detection time versus active and reactive power imbalance, (b) NDZ.**

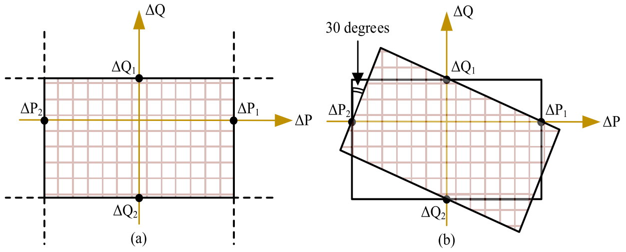


FIGURE 2. **NDZ region for (a) constant power load, (b) constant impedance load [20].**

islanding detection time of SGBMGs should be considered due to their mechanical inertia. After the islanding occurrence of SGBMGs, their voltage and frequency do not reach to their new values instantaneously [20], [21]. In the other words, it takes a longer time for large inertia SGBMGs to reach the operating thresholds of the relay [21]. Therefore, the dynamic behavior of voltage and frequency is very important in this case and islanding detection time should be carefully considered for NDZ extraction of SGBMGs. Fig. 1(a) shows the islanding detection time versus active and reactive power imbalances. Moreover, Fig. 1(b) illustrates the (ΔP, ΔQ) points for which the detection time becomes greater than a predefined threshold [22]. Based on IEEE 1547 standard, the maximum islanding detection time is 2 s for SGBMGs.

The NDZ boundary of SGBMGs may be affected by the governor and exciter controllers of SSSGs. Furthermore, the behavior of the SGBMG static loads (i.e. constant impedance, constant power, and constant current) and their dependency on voltage and frequency, as well as dynamic loads especially induction motors should be carefully investigated [23]. Generally, numerous transient simulations considering various scenarios should be performed for providing the relay NDZ [22]–[24]. For instance, about 195 various case studies are simulated by [24] around the perfect power imbalance to determine NDZ. Therefore, a simulation-based technique may be very time-consuming for determining the NDZ boundary. Moreover, using this method for adjusting the conventional relays settings is very difficult. Therefore, some analytical methods have been proposed in [20]–[23] to estimate the amount of NDZ of widely-used conventional techniques using some analytical functions. In the following paragraphs, a proper systematic method for extracting NDZ of SGBMGs is expressed which is developed by [20].

The typical shapes of NDZ for constant power and constant impedance loads are depicted in Fig. 2 [20]. As shown in this figure, the rectangle shape of NDZ can be considered for both constant power and constant impedance loads. However, for impedance loads, the rectangle should be rotated clockwise [20]. The rotation angle can be considered 30 degrees. It should be noted that ΔP_1 and ΔP_2 are mainly affected by the frequency-based relays settings. Besides, ΔQ_1 and ΔQ_2 are affected by the voltage-based relays thresholds. Parameters ΔP_1 and ΔP_2 can be easily determined using the analytical equations as presented in Table 2. Moreover, an iterative solution is suggested for determining the amount of ΔQ_1 and ΔQ_2 using the analytical synchronous machine equations whose detailed information is presented in [20].

TABLE 2. **Appropriate analytical functions for calculating minimum detectable active power mismatch [20].**

Technique	ΔP_1	ΔP_2
Over/Under frequency	$\Delta P_1 = \frac{2H.\beta}{f_0(t_d - \Delta t)}$	$\Delta P_2 = -\Delta P_1$
Rate of change of frequency	$\Delta P_1 = \frac{2H.\beta}{f_0}\left(1 - e^{-\frac{(t_d-\Delta t)}{T_f}}\right)^{-1}$	$\Delta P_2 = -\Delta P_1$
Vector shift	$\Delta P_1 = \frac{H}{\pi f_0}\left(\frac{-2\left(\pi^2 + 2\pi f_0(\beta-\pi)\right) - \sqrt{D_1}}{2t^2(\beta - 2\pi)}\right)$ $D_1 = 4\left(\pi^2 + 2\pi f_0 t(\beta-\pi)\right)^2 - 4\left(t^2(\beta-2\pi)\left(4\pi^2 f_0^2 + \beta\right)\right)^2$ $t = t_d - \Delta t$	$\Delta P_2 = -\Delta P_1$

β: relay setting, t_d: required islanding detection time, H: SSSG inertia, f_0: SGBMG nominal frequency, Δt: time delay, T_f: time constant of the preprocessing low pass filter (its typical value is 100 ms).

B. DETECTION TIME

Detection time is defined as the duration between the islanding occurrence instant and the relay detection instant. Some appropriate control and protection actions should be performed after islanding detection to maintain the SGBMGs stability [25]. Therefore, the amount of detection time should be small enough. Based on IEEE 1547, the detection time should be less than 2 s. However, for some SGBMGs, this time should be smaller than the standard criteria due to the stability and protection issues [23]–[26]. It is necessary to note that various islanding scenarios under different operating conditions should be investigated to evaluate the IDS detection time.

C. FALSE DETECTION RATIO

Islanding detection methods should stay secure during non-islanding events [27], [28]. To evaluate this, the false detection ratio (FDR) is defined as:

$$FDR = N_F / N_T \times 100 \tag{1}$$

where N_T is the total number of tested islanding or non-islanding scenarios and N_F is the number of false detection commands. The following conditions should be considered for evaluating the IDS:

- Load and capacitor switching: Large load or capacitor switching may result in the voltage, power, and frequency oscillations of the SGBMGs [29]. Therefore, the performance of IDSs should be evaluated under the maximum possible load or capacitor switching.
- Induction motor starting: Starting of large induction motors, especially using direct online (DOL) methods lead to reactive power consumption increment and voltage drop in the SGBMGs. In addition, the seen reactance from SSSGs terminal changes during motor starting. Therefore, IDSs may operate incorrectly in this condition [30].
- Various short circuit fault conditions: Due to fault ride through requirements of SSSGs, IDSs should remain secure during short circuit events.
- Cold load pickup: Re-energization of a distribution feeder after a long duration of power interruption, which is called ‘‘cold load pickup’’, may lead to an overcurrent and under voltage phenomenon, simultaneously. This condition should be considered for evaluation of IDS performance.
- Fault-induced delayed voltage recovery (FIDVR): FIDVR phenomenon is a severe condition where the voltage magnitude of distribution feeders remains low for about 3-30 s due to the large slip of induction motors after short circuit clearance. It should be noted that FIDVR usually takes place at feeders with a high amount of induction motors penetration. The IDS should remain secure during recoverable and unrecoverable FIDVR conditions [31].
- SGBMG stable or unstable power swing: On the contrary of IBMGs, stable or unstable power swings may occur for SGBMGs due to various events especially short circuit faults. Therefore, it is important to evaluate the IDS of SGBMGs in this condition [32].
- Fault-initiated islanding: This condition occurs when the point of common coupling (PCC) breaker is opened by the protective devices due to upstream network faults. In this condition and after opening the PCC breaker, the IDS should realize the islanding condition [33].

D. NON-DETECTION INDEX

Non-detection index (NDI) is proposed by [34] to evaluate the effectiveness of an IDS to detect islanding events for a specific SGBMG. Depending on the SGBMGs specifications, upstream system configuration, and load characteristics, an IDS can be suitable or non-suitable for a specific SGBMG. Therefore, for some SGBMGs simple low-cost conventional IDS is appropriate for islanding detection. However, for some SGBMGs more complex IDS should be employed. NDI can help engineers to employ the most suitable IDS for the SGBMGs.

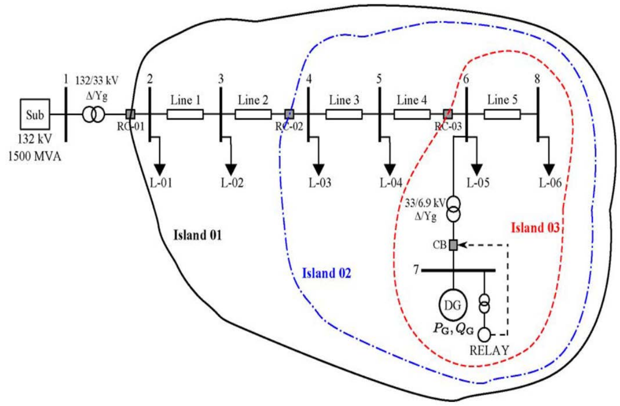


FIGURE 3. Sample test system [34].

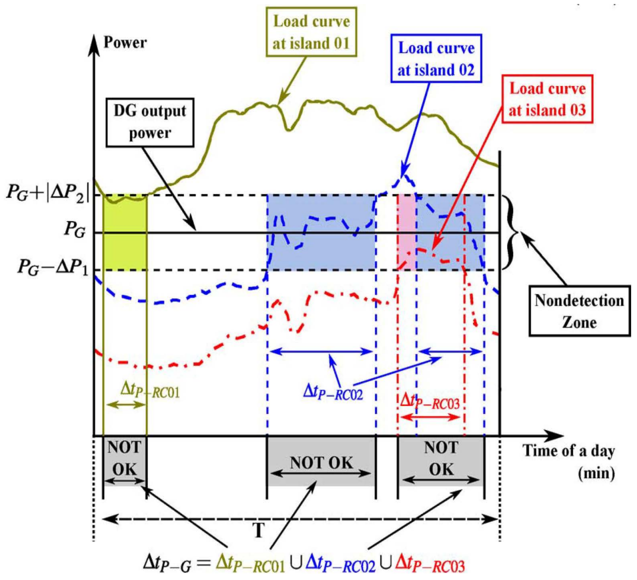


FIGURE 4. Example of non-detectable periods [34].

To explain NDI, the test system shown in Fig. 3 is considered [34]. The SSSG can be separated from the upstream grid by the opening of various breakers. For the system shown in Fig. 3, the opening of breakers RC01, RC02 and RC03 makes Island 01, Island 02, and Island 03, respectively. In addition, the consumption curve of islanded system load for each case is illustrated in Fig. 4. The relay NDZ band is shown by ΔP_1 and ΔP_2 in this figure. As shown, for some time periods, the power mismatch (ΔP) may locate in the relay NDZ where the relay cannot detect islanding events. For instance, within the Δt_{P-RC01} period, the load curve of island 01 is located in the relay NDZ band and thus, the islanding condition of island 01 cannot be detected by the relay within this period. Finally, the total time in which the relay fails to detect islanding events can be obtained by (2) considering various islanding situations:

$$\Delta t_{P-G} = \Delta t_{P-RC01} \cup \Delta t_{P-RC02} \cup \cdots \cup \Delta t_{P-RC0n} \quad (2)$$

Consequently, NDI can be obtained by (3) for a specific period (T):

$$NDI = \Delta t_{P-G}/T \tag{3}$$

E. UNSYMMETRICAL LOSS OF MAIN DETECTION

Loss of main may occur in one phase or two phases due to unsymmetrical operation of upstream operation devices especially fuses. In addition, unsymmetrical loss of main may occur due to broken conductors [35]. Therefore, the unsymmetrical loss of main can be categorized as an open circuit fault at the upstream system. On the other hand, this unsymmetrical loss of main leads to a negative sequence current which may cause SSSG thermal damages. It should be noted that the location of this unsymmetrical loss of main (i.e. unsymmetrical open circuit) has a significant impact on the amount of this negative sequence current. In such a condition, the islanding signal should be issued and the proper control and protection actions should be performed to retain SGBMG stability and prevent thermal damages caused by the negative sequence current. Therefore, the capability of unsymmetrical islanding detection is an important feature which should be evaluated for IDS.

III. ISLANDING DETECTION METHODS FOR SGBMGs

Various approaches have been proposed in the literature to detect islanding conditions of SGBMGs which can be divided into local and remote methods, as shown in Fig. 5 [11]–[16], [36]. Local methods operate based on local measurements at DG or PCC location; whereas the remote methods detect the islanding condition using the transferred information from various points by a proper communication link. The most advantage of remote methods is to eliminate none detection zone (NDZ). However, local methods are more preferred by the researchers due to economic concerns. In the following, the existing local and remote approaches applicable to SGBMGs are investigated.

A. REMOTE METHODS

The main requirement of remote methods is the communication link between the DGs and remote equipment to transfer a signal which helps IDS to detect islanding events [36]. The remote methods are applicable to both SGBMGs and IBMGs. The major advantage of remote methods is their zero NDZ [36]. As shown in Fig. 5, remote methods can be divided into four major groups. The power line carrier (PLC) is employed by some remote methods to transmit a signal from the upstream substation [37]. In this method, a high-frequency signal would be continuously injected into power lines. This signal is detected by a proper receiver at the SSSG location [38]. The islanding condition will be realized when the receiver cannot detect the injected signal [38], [39]. However, this method is not economical for small-scale SGBMGs due to the high implementation cost of PLC. Supervisory control and data acquisition (SCADA) can be employed to detect islanding events of SGBMGs [40].

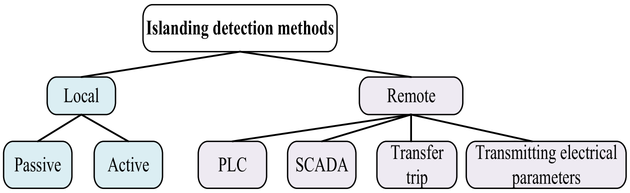


FIGURE 5. Classification of islanding detection methods.

SCADA measures upstream system electrical parameters including voltage and current at various locations through appropriate communication media [41]. The main shortcomings of this method are large detection delay and high dependency on the communication link [42]. Nowadays, the SCADA-based IDSs can be implemented easily in the smart distribution system which is equipped with advanced distribution management system (ADMS) platform [43]. ADMS is an integrated central platform which includes advanced control and protection functions. This platform has a high-speed and secure connection to all of the system intelligent electrical devices (IEDs) and remote-controlled switches (RCSs). Therefore, islanding condition can be easily detected in each part of the system by gathering the information of these IEDs and RCSs through the ADMS platform. In addition, ADMS can significantly improve the IDS speed by utilizing new features of IEC-61850 protocol like GOOSE messages. However, implementing such a platform requires high bandwidth communication media which makes this technique expensive [43].

To lessen the implementation cost, some of the new islanding detection methods employ few electrical parameters which require a simple communication media. For instance, synchronized phase voltages measured at the upstream point and SGBMG is proposed by [36] to detect the islanding event. In this method, synchronized measurement units (SMUs) are utilized to collect and transmit the required data. In addition, a signal time tag is provided by a GPS device. In [44], micro-phasor measurement units (μPMUs) are employed to provide the frequency and phase angle information of the DGs terminal and reference substation. Then, the cumulative sum of frequency and angle difference is employed to detect islanding condition.

To decrease the amount of transferred data, transfer trip schemes are employed in various distribution systems. Transfer trip schemes operate based on monitoring the state of upstream breakers and reclosers. If a switch becomes open, the IDS should check the islanding condition [45]–[47]. To do so, the configuration of the upstream system is required to check the islanding of SGBMGs. Therefore, it is recommended to utilize this method along with SCADA or ADMS platform to provide appropriate performance [43]. Various communication infrastructures can be employed to provide fast operation of transfer trip schemes including optical fiber, and cellular data such as general packet radio service (GPRS), 2G, 3G, and other wireless communications. However, some of these communication technologies may not be secure against cyber-attacks. Therefore, a proper communication protocol should be utilized for fast and reliable communication. Recently, this requirement can be provided using IEC 61850 protocol and its GOOSE message capability [43], [46]. However, if the number of switches between SGBMG and upstream substation is large, the implementation of this method would be very complex [47].

B. LOCAL METHODS

The local methods operate based on local measurement of proper signals on the SGBMGs side without using any communication link. These methods are traditionally classified into active and passive methods [13]–[16]. Active methods operate based on injecting an intentional disturbance to SGBMG which pushes the voltage and frequency to become lower or greater than a permissible threshold after the islanding occurrence. It should be noted that this disturbance can be applied to the SSSG voltage control system, and/or the SSSG frequency control system or by switching some loads in the SGBMGs feeders [13], [14], [16]. However, passive methods only monitor some predefined indices or extract various hidden features to distinguish islanding condition without injecting any disturbance to the SGBMG. Local methods are investigated in the following sections.

IV. ACTIVE ISLANDING DETECTION METHODS FOR SGBMGs

As expressed in the previous sections, active methods are commonly utilized for detecting the islanding conditions of IBMGs, and these methods are not recommended for SGBMGs due to the following reasons:

- Loss of the chance of smooth transition between grid-connected and islanding operation modes,
- Increasing SSSG mechanical damages and fatigue during both steady-state operation and transient events,
- Decreasing the lifetime of the SSSG and MG equipment and increasing maintenance and overhaul costs,
- Increasing the possibility of SSSG transient instability during non-islanding events.

The SGBMGs active islanding detection methods can be divided into three major groups including impedance switching, opening or closing of the microgrid circuit breakers, and applying perturbation signals into the SSSG control loops such as governor and automatic voltage regulator (AVR) [48]–[51]. The first group (i.e., impedance switching) has a lower adverse impact on the SSSG stability and its mechanical fatigue. Meanwhile, the third group may be much more effective for detecting the islanding condition. To take the whole benefits of active methods and increase their performance, these methods are commonly utilized along with a suitable passive method which is called a hybrid technique [48]–[50]. Passive methods are commonly utilized for initiating the intentional disturbances or analyzing the MGs signal after applying such perturbations. In this section, proper active methods which can be applied to SGBMGs are investigated. The overall flowchart of active/hybrid techniques is depicted in Fig. 6. As shown, some intentional perturbations are injected into the SGBMG at the specified time intervals (or after detecting a possible islanding event). Then, to distinguish islanding events from others, the suitable parameters of SGBMG and passive indices will be monitored and compared with the predefined thresholds. It should be noted that these thresholds are determined using the offline calculations part. Due to the adverse effects and excessive implementation costs of active/hybrid methods, only a few numbers of these techniques have been proposed for SGBMGs. Some of these methods which can be applied to SGBMGs are presented in Table 3. These methods are expressed in the following paragraphs.

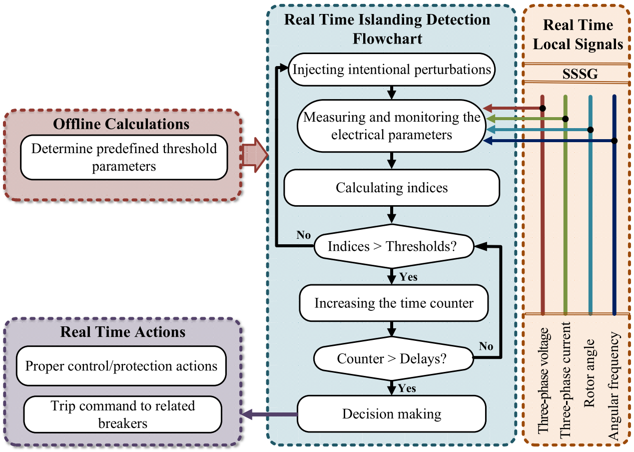


FIGURE 6. IDS flowchart for active methods.

TABLE 3. Comparing performance of various active IDSs.

Ref.	Technique	NDZ	Speed	FDR	Description
[48]	Open-close of the SSSG circuit breaker	0%	300ms	Low	For SSSGs
[49]	Capacitor switching	0%	600ms	Medium	For both IBRs and SSSGs
[50]	Injecting perturbations into the SSSG active/reactive power control loops	0%	200ms	Low	For SSSGs
[51]	R-L load switching	1.67%	440ms	Medium	For both IBRs and SSSGs

The open-close of the SSSG circuit breaker at the connection point is proposed by [48] to detect SSSG islanding events during a small power mismatch. In this method, one phase of the SSSG CB is opened and closed immediately which leads to significant changes in the SSSG terminal and exciter voltages. Then, the rate of change of exciter voltage (RCEV) is employed as an index to detect islanding conditions. For islanding events, the amount of this index would be greater than a predefined threshold. The detection time of this method is about 300ms with zero amount of NDZ. However, this open-close may occur for each islanding or non-islanding event, even load switching, which results in high mechanical fatigue of the SSSG and circuit breaker. Moreover, single-pole opening and closing results in large magnitude negative sequences which have adverse effects on the system, especially SSSG. On the other hand, single-pole open-close of the SSSG circuit breaker increases the possibility of SSSG transient instability.

In [49], an IDS is proposed to detect SSSG islanding events using the capacitor switching technique. At first, the capacitor rated power is determined based on the systematic approach. The minimum power of this capacitor bank can be analytically determined based on the maximum amounts of positive and negative reactive power mismatches for which the conventional relays cannot detect the islanding condition. This capacitor is inserted after opening the main breaker to increase the power mismatch and thus, the islanding events can be detected by voltage or frequency relays. The detection time of this method is less than 600 ms and its NDZ value is almost zero due to the capacitor insertion. However, this method may fail to effectively insert the capacitor bank when the islanding occurs due to opening a breaker in the upstream distribution system.

In [50], a perturbation signal would be injected into the SSSG active/reactive power control loops to create intentional instability during islanding events which leads to the significant undamped variations of the SGBMG frequency and voltage signals. Then, the voltage and frequency signals are processed through a signal processing unit, which is called multiple signal classification, and the islanding would be concluded if the undamped variations of voltage or frequency signals are detected. If the autonomous operation of SGBMG after islanding detection is required, the controller parameters will be changed by this method at the islanding detection instant. However, the islanded SSSG may lose its stability due to the injected intentional perturbations into the SSSG controller loops, and thus, the chance of creating a stable islanded SGBMG may be lost. The detection time of this method highly depends on the SSSG control system. The islanding condition considering zero power mismatch can be detected in 200 ms for a droop control system. However, for constant power control and zero power mismatch the islanding detection time are about 1.5 to 2 s.

The rate of change of reactive power (*dq/dt*) is employed by [51] to initiate R-L load switching during possible islanding events. After load switching, the amount of *dq/dt* is calculated again to realize the islanding condition. In this method, a suitable circuit breaker or solenoid contactor can be employed for switching the R-L load. However, using this method may not be beneficial due to its high expenditure. In addition, this method may fail to distinguish some types of short circuits (especially three-phase) from islanding events. Moreover, the proposed strategy may insert the R-L load during some non-islanding events (especially short circuits) which may result in SSSG instability. The detection time of this method is about 440 ms and its NDZ is greater than zero. Therefore, the performance of this method in comparison to the other active methods is not suitable.

Based on our simulation studies and with reference to the investigations provided by [52], the frequency of SGBMG changes monotonically after islanding occurrence without requiring any intentional disturbance, as shown in Fig. 7. On the other hand, using active methods for SGBMGs has an adverse impact on the SGBMG transient stability and SGBMG power quality. Therefore, as explained before, passive methods are more preferred for islanding detection of SGBMGs, and active methods are not recommended for these types of MGs [14]. Consequently, mainly the passive methods are investigated in the rest of the paper.

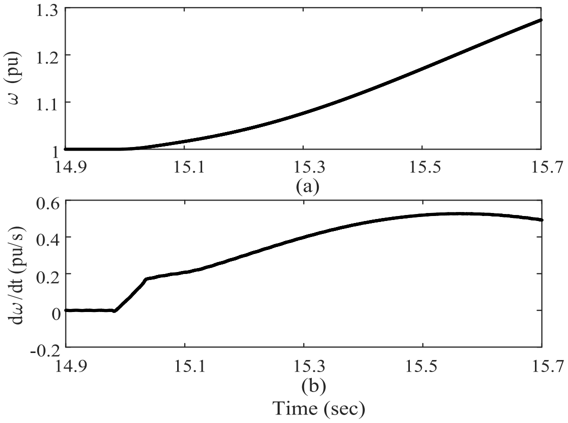


FIGURE 7. Simulation results for an islanding scenario (a) SGBMG frequency, (b) rate of change of SGBMG frequency.

V. PASSIVE ISLANDING DETECTION METHODS FOR SGBMGs

The passive methods are the first techniques employed to detect SGBMGs islanding detection condition. The conventional passive methods have a high non-detection zone and false decision ratio. To improve the performance of the conventional methods, various rules and algorithms are proposed by different researchers which are explained in the following sub-sections.

A. SETTING RULES FOR ADJUSTING CONVENTIONAL RELAYS

The common commercial islanding detection methods which are conventionally utilized include 1) over/under voltage (OV/UV), 2) over/under frequency (OF/UF), 3) rate of change of frequency (ROCOF) and, 4) vector shift (VS). These methods suffer from the high amount of NDZ and FDR. In addition, the performance of these methods highly depends on the adjusted setting values [53], [54]. Therefore, using appropriate values for the setting parameters can effectively improve the performance of these methods. Some articles have investigated the impact of setting values

TABLE 4. **Comparing performance of various IDSs based on monitoring proper indices.**

Ref.	Technique	Threshold	NDZ	Speed	FDR	Unsymmetrical detection	Description
[57]	Equivalent resistance with respect to time	Constant	1%	173ms	Medium	No	For both inverter based resources (IBRs) and SSSGs
[58]	Rate of change of power factor angle	Adaptive	0.5%	<100ms	Low	No	For both IBRs and SSSGs
[59]	Rate of change of frequency over reactive power	Constant	1.65%	200ms	Medium	No	For both IBRs and SSSGs
[60]	Estimating the parameters of a linear model of the distribution system	Constant	NR	NR	Medium	No	For both IBRs and SSSGs
[61]	sequence superimposed component of impedance	Constant	0%	20ms	High	Yes	For both IBRs and SSSGs
[62]	Reactive power rate of change	Constant	NR	100ms	Medium	Yes	For SSSGs
[63]	Rate of change of impedance	Constant	3.4%	70ms	Low	Yes	For SSSGs
[64]	Phase angle between the positive-sequence components of voltage and current	Constant	<0.1%	20ms	Low	No	For both IBRs and SSSGs
[24]	Equivalent resistance with respect to angular frequency	Adaptive	0.2%	<250ms	Low	No	For SSSGs
[65]	Rate of change of sequence components of currents	Constant	0%	NR	Medium	Yes	For both IBRs and SSSGs

on the performance of the conventional methods which are described in the following.

In [55], a new setting rule is proposed employing a data-mining technique to determine the optimal threshold values of common commercial islanding detection functions. In this method, the amount of NDZ and false operations are minimized for each SSSG. For a sample SSSG, the optimal settings values of UF, ROCOF, and UV are proposed to be equal to 0.9975pu, 0.035pu/s, and 0.915pu, respectively.

A new graphical approach is proposed in [56] to adjust the threshold values of anti-islanding frequency-based relays to disconnect the SSSG after islanding occurrence or during abnormal frequencies. To do so, a graphical power mismatch region is defined to minimize the relay NDZ and its nuisance tripping. For a specific SSSG, the threshold value of ROCOF is suggested to be 0.0083 pu/s with 330 ms seconds operation delay.

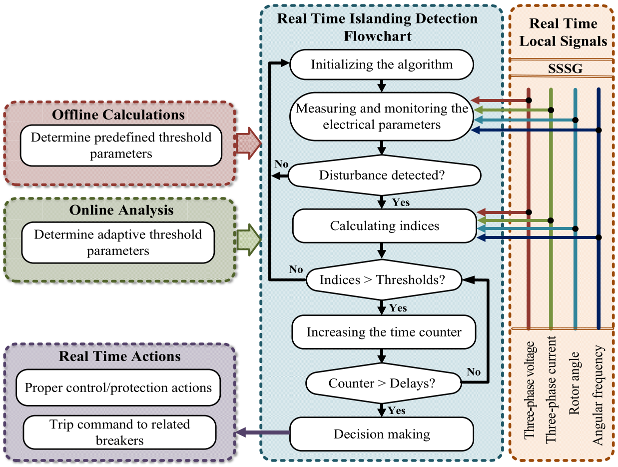


FIGURE 8. **IDS flowchart based on monitoring proper indices.**

B. MONITORING PROPER INDICES

These types of methods are widely utilized by the SGBMGs. The overall decision-making flowchart of these methods is illustrated in Fig. 8 which can be divided into various parts as described in the following. As shown in this figure, real-time local signals of SSSG including voltage, current, rotor angle, and angular frequency are utilized as the input of the real-time islanding detection flowchart which is the main part of the decision-making process. In this part, the first step is employed to initialize the algorithm parameters. Then, second step is used to detect the system disturbances and initiate the main algorithm. It should be noted that the second step may be overlooked for some of the detection methods. The third step is utilized to calculate the indices based on the pre-defined procedure. In the final step, the calculated indices are compared to the corresponding thresholds and the islanding events are detected after elapsing the considered intentional time delay. This time delay may be neglected for some methods. It should be noted that the predefined thresholds are determined using offline calculations part. Meanwhile, in some islanding detection methods, the required thresholds are not a constant value. For these methods, the thresholds are adaptively determined using online analysis part. After islanding detection, the proper real time actions, e.g. trip command to breakers and proper control/protection actions would be performed.

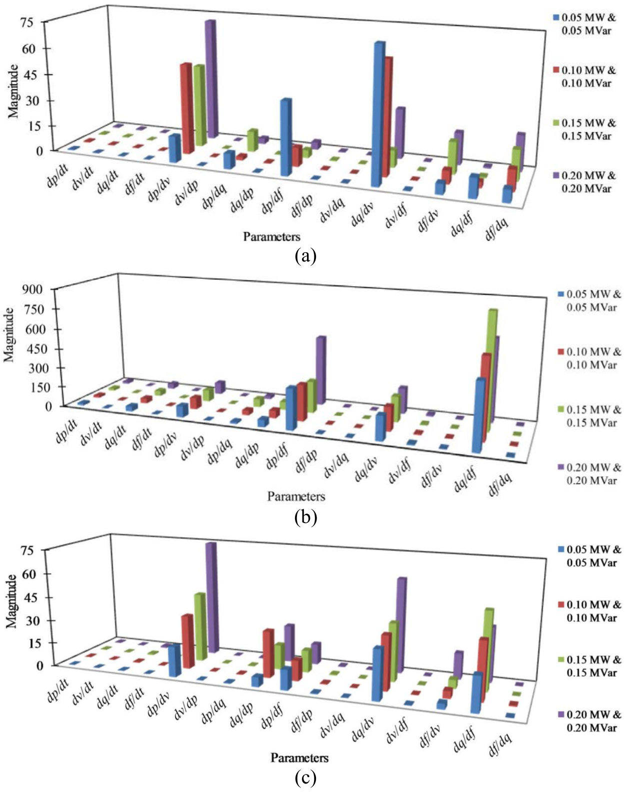
Various types of these islanding detection methods and their performance are presented in Table 4 [57]–[65].

They are mainly proposed to overcome the shortcomings of conventional methods. Some of these methods are expressed in the following paragraphs.

In [59] and [66], the sensitivity of various indices and parameters which are proposed by literatures are investigated during various islanding and non-islanding events. These indices are tabulated in Table 5. The simulation studies performed by [66] reveal these indices may have changes during both types of islanding and non-islanding events. The variations of these indices during various islanding scenarios and non-islanding events (including load switching and fault events) are depicted in Fig. 9. In addition, the amount of SGBMG power mismatch for each simulation case is shown in this figure. As shown in Fig. 9(a), only *dp/dq*, *dq/dp*, *dq/df*, *dq/dv*, *dv/df*, *df/dq* and *dp/dv* have significant changes during islanding events and the other indices do not change considerably. Furthermore, the aforementioned parameters, except *dq/df*, have large variations during various non-islanding events, as shown in Figs. 9(b) and 9(c). Therefore, *dq/df*, which has large variations during islanding events and small changes during non-islanding events, may be more appropriate than the other ones to differentiate islanding events from non-islanding events. However, distinguishing islanding and non-islanding events using these indices and pre-defined thresholds is very difficult and thus, the amount of FDR would be high. In addition, the dynamic behavior of loads, especially induction motors is neglected by most islanding detection methods, and these methods only focus on a constant RLC load [51], [54], [59], [66], [67]. Moreover, the performance of these methods highly depends on the predefined constant threshold values.

TABLE 5. Various indices used for islanding detection [59].

Passive parameters
Rate of change of active power (*dp/dt*)
Rate of change of frequency (*df/dt*)
Rate of change of reactive power (*dq/dt*)
Rate of change of voltage (*dv/dt*)
Rate of change of reactive power over active power (*dq/dp*)
Rate of change of reactive power over voltage (*dq/dv*)
Rate of change of frequency over reactive power (*df/dq*)
Rate of change of voltage over active power (*dv/dp*)
Rate of change of active power over reactive power (*dp/dq*)
Rate of change of voltage over reactive power (*dv/dq*)
Rate of change of reactive power over frequency (*dq/df*)
Rate of change of active power over voltage (*dp/dv*)
Rate of change of active power over frequency (*dp/df*)
Rate of change of voltage over frequency (*dv/df*)
Rate of change of frequency over active power (*df/dp*)
Rate of change of frequency over voltage (*df/dv*)



(a)
(b)
(c)

FIGURE 9. Variations of passive indices during (a) islanding event, (b) non-islanding short circuit event, (c) non-islanding load increment event [66].

Therefore, to increase the sensitivity of passive methods and enhance their security, applying adaptive thresholds and investigating the impact of load dynamic behavior are recommended by [24], [57], [58]. For instance, derivative of the equivalent resistance seen from DG terminal with respect to angular frequency is proposed by [24] to detect islanding condition. When the amount of the proposed index becomes greater than the adaptively determined threshold, the islanding condition would be realized. The amount of adaptive threshold is analytically calculated considering the dynamic behavior of loads. The value of calculated threshold is very large during non-islanding events. However, it becomes small during islanding events which significantly helps improve the algorithm security. In [58], an adaptive threshold is adopted using the relation of the resonant frequency of load and its reactive power consumption. This can improve the algorithm security during motor starting condition. Furthermore, based on our simulation investigations, the algorithms with adaptive thresholds have smaller FDRs, as shown in Table 4. For instance, both of the methods which are presented by [24] and [57] operate based on equivalent resistance.

However, usage of the adaptive thresholds by [24] prevents its maloperation during non-islanding events, especially three-phase short circuits. As shown in Fig. 10, the method proposed by [57] operates incorrectly during a three-phase short circuit fault while the method proposed by [24] remains secure.

C. FEATURE EXTRACTION AND SIGNAL PROCESSING METHODS

To lessen the NDZ value and islanding detection time, hidden features of system electrical parameters including voltage, current, and frequency are extracted using various

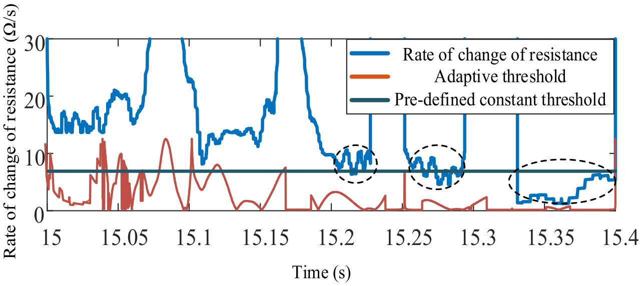


FIGURE 10. Simulation results for non-islanding short circuit scenario for both adaptive and constant threshold values.

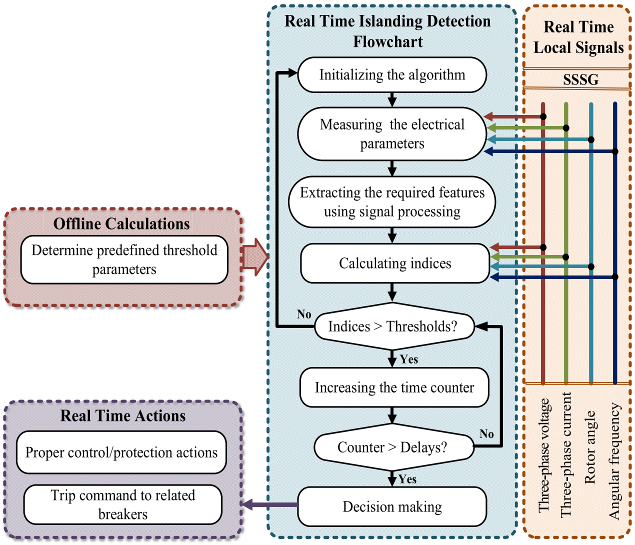


FIGURE 11. Flowchart of feature extracting based IDS methods.

signal processing methods [68], [69]. The general flowchart of feature extraction-based methods is depicted in Fig. 11. Similar to the previous method, real time local signals of SSSG including voltage, current, rotor angle and angular frequency are utilized as the inputs of the real time islanding detection flowchart, as shown in Fig. 11. In this part, the required features of the input signals would be extracted using signal processing techniques. Then, new indices are calculated based on these extracted features. Finally, these indices are compared to the predefined thresholds and the islanding events are detected after elapsing the considered intentional time delay. It should be noted that the predefined thresholds are determined using offline calculations part.

In this section, various signal processing-based IDSs are described and some of them are presented in Table 6 [70]–[78]. A comprehensive summary of these signal processing techniques is described in the following.

Fourier transform (FT) is one of the most common frequency-domain techniques which is usually employed to extract the various harmonics of the input signals especially voltage and current [79]. However, harmonic-based methods are effective mainly for inverter-based microgrids. Since harmonic content extraction is not helpful for detecting the islanding events of SGBMGs and FT-based methods cannot extract the transient information of the input signals, these methods may not be suitable for SGBMGs [79]. To cope with this issue and to extract the transient features of the input signals, other signal processing methods like modified FT and wavelet transform (WT) are recommended [80]. These methods can decompose the input signal into various frequency bands [81]. WT extracts the signal information in both time and frequency domains [81], [82]. However, FT only describes the frequency domain information of the input signal [81]–[84]. It should be noted that WT-based methods employ small windows to extract high frequencies and large windows for low-frequency features [84]. For instance, WT technique is employed by [77] to extract the high-frequency components of microgrid voltage and frequency at islanding instant. Then, if the amount of these high-frequency contents becomes greater than a predefined threshold, the islanding condition would be realized in less than 1 s. It should be noted that this method may operate incorrectly during non-islanding events.

WT method may operate incorrectly due to measurement equipment transients or system high-frequency noise. To overcome the disadvantages of WT-based methods and improve their security against noise, wavelet singular entropy (WSE) technique is recommended [73]. In this method, the three-phase voltage signals are measured at DG terminals. These signals are processed by WT and the associated coefficient matrix is generated. Based on this, the singular value matrix and probability array are computed. Then, the amount of WSE will be calculated for each phase. Finally, the linear summation of each phase WSE is employed as an effective index to detect loss of main [73]. This approach can reduce the NDZ value to almost zero and minimize the detection time. However, the main disadvantages of this method include heavy computational burden and maloperation during non-islanding disturbances especially DG transient instability.

To enhance the WT performance, a modified version of WT called S-transform (ST) is developed by [85]–[88]. Generally, ST can be considered as a combination of WT and short-time FT (STFT). ST gives both amplitude and phase information for a wide spectrum of the input signal and provides frequency-dependent resolution. However, ST may fail to localize some disturbances in the time domain [82]. To cope with this issue, the modified version of ST which is named Hyperbolic ST (HST) is adopted [83]. HST employs a pseudo-Gaussian hyperbolic window which has a better resolution at various frequencies. In [89], the HST technique is utilized to process the PCC voltage signal. Then, the signal energy is determined based on the extracted components. Finally, the islanding condition is realized when the computed energy becomes greater than a predefined threshold. Our simulation studies and the investigations of reference [81] shows HST has better performance against noisy signals and also it has a better resolution for detecting islanding events compared to ST and WT. Moreover, the HST-based algorithms are more secure against non-islanding events.

TABLE 6. Comparing various feature extraction based IDSs.

Ref	Extraction method	Input signal	NDZ	Speed	FDR	Multi-phase detection	Description
[70]	TVF-EMD	Voltage	0%	15ms	Medium	No	Both SSSGs and IBRs
[71]	HHT	Angular frequency	<0.05%	<450ms	Low	No	SSSGs
[72]	Tufts-Kumaresan	Angular frequency	0.5%	611.5ms	Low	No	SSSGs
[73]	WT	DG voltage	0%	Half cycle	Medium	Yes	Both SSSGs and IBRs
[74]	TMF	Voltage	1%	55ms	Medium	Yes	Both SSSGs and IBRs
[75]	MM	Negative sequence voltage	0%	15ms	Low	Yes	Hybrid
[76]	TMF	DG voltage and current	0%	<1 Cycle	Medium	No	Both SSSGs and IBRs
[77]	WT	Voltage and frequency	---	<1s	Medium	No	SSSGs
[78]	HHT	PCC voltage and current	5%	<2 cycle	Medium	No	SSSGs

The empirical mode decomposition (EMD) is also employed by several research works to detect islanding condition [70], [90]. This method decomposes the input signal into various mono-components which are known as meaningful intrinsic mode functions (IMFs) [91]. However, this method suffers from various issues including computational complexity and mode mixing effect [70], [90], [91]. To overcome these issues, time-varying filter-based EMD (TVF-EMD) is recommended by [70], [91]. In fact, the cutoff frequency of the TVF-EMD filter is not a constant value which enhances the decomposition performance, especially for nonstationary signals. In [70], TVF-EMD is employed to compute the energy amount of IMFs. If the calculated energy becomes greater than a predefined threshold, the islanding event would be concluded. The false detection rate of this method during islanding and non-islanding events are 0.056% and 1.96%, respectively. Moreover, this method can properly realize islanding condition within 15ms during zero power mismatch. Although the computation of TVF-EMD has some complexities, reference [70] claims that TVF-EMD methods can be practically implemented using the new digital relays. A new EMD-based technique, called Hilbert–Huang transform (HHT), is developed recently to analyze nonlinear and non-stationary time-domain signals. In fact, HHT decomposes the signal using frequency and amplitude modulation through the aforementioned EMD process. In [71], HHT process is employed to analyze the SSSG dynamic response and then, four major features including damping factor, zero mode, identity participation matrix and frequency of oscillations will be checked to distinguish the islanding events from non-islanding disturbances. This method can detect the islanding event within 450ms and its NDZ amount is less than 0.05%.

To enhance time localization of the processed signal, especially for high frequencies components, the time-time transform (TTT) technique is also recommended by some literatures [92]–[94] which is computed using inverse Fourier transform of the ST filter [81]. Meanwhile, its computation has some complexities similar to EMD. Another powerful signal processing method which has a low computational burden is mathematical morphology (MM). MM is a time-domain nonlinear transformation that is adopted based on set theory and integral geometry [95]. The input signal can be easily processed through MM using some simple operators including Dilation and Erosion [96], [97]. These operators work based on set theory and simple addition or subtraction and thus, the associated computational burden is very low. In [75], an islanding detection method is proposed using MM to detect the islanding event of each DG in a hybrid microgrid. To do so, the three-phase voltage and current signals at target DG are acquired for 1 cycle. Then, these signals are processed through MM filters using simple operators including Erosion, Dilation, Opening, and Closing. Afterward, some islanding detection indices would be computed using the MM output. If the amount of indices becomes greater than a pre-specified threshold, the islanding event will be detected. The islanding event can be detected using the method within 15ms and its NDZ amount is almost zero.

Transient monitoring function (TMF) is another signal processing technique which can be employed to distinguish islanding events from non-islanding ones [74]. This method determines the difference between the real measured signal and estimated signal assuming the system operates under normal grid-connected mode [74]. The large values of the computed difference indicate the islanding condition. The main concern for this method is to estimate the required

TABLE 7. Comparing various intelligent based IDSs.

Ref	Method	Inputs	NDZ	Speed	FDR	Multi-phase detection	Description
[99]	DT	27 features	<30%	1.5 cycles	High	No	Both SSSGs and IBRs
[100]	DT & FR	11 features	<40%	---	Medium	No	SSSGs
[101]	RF	---	<30%	---	Medium	No	Both SSSGs and IBRs
[102]	EkNN	---	0%	70ms	Low	No	Both SSSGs and IBRs
[103]	ELM	Phase space method	---	6 cycles	Low	No	Both SSSGs and IBRs
[104]	DT	11 indices	0%	45ms	Medium	No	SSSGs
[105]	DT	11 indices	---	163.7ms	Medium	No	SSSGs
[106]	DT	Harmonic content df/dt	0%	300ms	Low	No	SSSGs

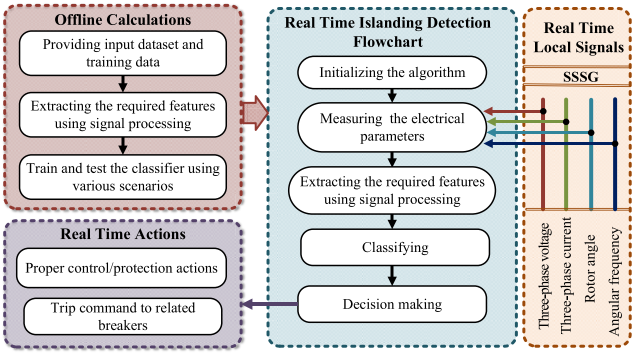


FIGURE 12. Flowchart of intelligent IDS methods.

signal accurately. Moreover, this method may operate incorrectly during non-islanding events, especially three-phase short circuits. The NDZ amount and islanding detection of this method is about 1% and 55ms, respectively.

D. INTELLIGENT TECHNIQUES

To enhance the performance of islanding detection methods, intelligent-based techniques have been employed along with the indices introduced in section IV.B and signal processing methods presented in section IV.C. The algorithm flowchart of this method is illustrated in Fig. 12. As shown in this figure, some indices or signal processing techniques are utilized to extract the suitable features. Then, these extracted features would be utilized to train and test the intelligent-based classifiers. Finally, these trained classifiers are utilized in real time flowchart to distinguish islanding events from non-islanding events. The main part of intelligent-based methods is selecting the appropriate features which can effectively distinguish islanding events from non-islanding ones. Therefore, the most sensitive features to islanding events should be selected. Moreover, to lessen the computational burden and enhance the detection speed, the correlation between the selected features should be minimized [98].

The type of classifier has a significant impact on the islanding detection performance. Various classifiers are recommended by the prior works for islanding detection. The performance of some of the intelligent-based IDSs and their utilized classifiers are compared in Table 7. These methods are described in the following [99]–[106].

Decision tree (DT) is the most common data mining-based technique which provides a hierarchical decision-making model [99]. In fact, DT converts complex decisions into some simple decisions by employing “if-then” rules. These rules should be carefully extracted from the segmentation of the input data [106]. DT classification begins at the “Root node” which includes the initial classification. This node is splattered into some “Child nodes” by using the proper classifications [106]. These conversions would be continued till the final decision or “Leaf node” is achieved. A DT-based islanding detection scheme is proposed in [98] which employs 27 different features. However, this method suffers from large NDZ value due to using low sensitive features. To improve the IDS performance, the harmonic content of equivalent reactance is utilized as a new input feature by [106]. Then, a new relay logic is developed using a classification and regression tree (CART). The NDZ value of this method is almost zero and its detection time is about 300ms.

Fuzzy logic (FL) is a computational approach which is employed by various articles to detect islanding condition. In the other words, FL is a powerful technique to resolve problems based on the associated truth degree [100]. For instance, in [100] a new FL-based method is developed which employs 11 system features including ROCOF to detect the islanding condition of SGBMGs. In addition, the DT-based method is utilized to determine the initial classification boundaries. This method can detect the islanding condition when the power mismatch becomes greater than 40%. Moreover, it has good performance under 20 and 30 dB noise conditions.

Artificial neural network (ANN) is one of the main intelligent techniques which is basically employed for machine learning. Various components including analytical functions and different layers are utilized by ANN-based methods to learn a pattern from the input data. After the training process, ANN can recognize the pattern of the new input data. For islanding detection purposes, some microgrid features should be employed as training or testing inputs. Therefore, various system conditions should be considered for training ANN-based IDSs. If some of the system conditions are not considered in the training stage, the ANN technique may operate incorrectly during the un-experienced islanding or non-islanding events. In [107], a four-layer ANN technique is utilized for islanding detection and the measured voltage signals at DG terminals are injected for training and testing procedures. About 2000 simulations including islanding and non-islanding scenarios have been performed for various operating conditions. Four different cases are considered for islanding scenarios, including positive/negative active/reactive power mismatch. Moreover, as the non-islanding events, load switching and frequency variations are simulated. However, some other conditions especially fault-initiated islanding and dynamic behavior of induction motors are not considered. The operation time and NDZ value of this method are 2.75 s and 10%, respectively [107]. An adaptive combination of FL and ANN techniques are recommended by several articles to enhance the islanding detection accuracy which is called "ANFIS" [108].

A new NN-based classifier called "extreme learning machine (ELM)" is developed to enhance the speed of conventional NN-based classifiers [103]. In fact, ELM is a "randomized single-hidden layer feed-forward neural network" which can be effectively utilized for islanding detection purposes. For instance, ELM is employed by [103] in which the ELM optimal parameter settings are specified using "evolutionary computation" [103]. In this method, the input features would be obtained using phase-space method. The false detection rate of this method is very low and its detection time is about 6 cycles. Furthermore, an ensemble learning method named random forest (RF) classifier is employed by [101] to detect islanding detection which operates based on various decision trees and its islanding detection performance is presented in Table 7.

Support-vector machine (SVM) is a powerful machine learning tool which can be employed for both classification and regression purposes [109]. SVM basically operates based on separating hyperplanes. To classify the input data with the minimum failure, the proper hyperplane should be determined using various linear or non-linear kernel functions. In [110] an intelligent method is developed using SVM to improve the performance of VS technique. In this method, some features are extracted using five system variables. These features are injected into the SVM classifier as inputs. The performance of the proposed method is explored using different kernels including Gaussian RBF, polynomial and linear. These investigations reveal the NDZ of this method is almost zero. In addition, its detection accuracy for 0.5% power mismatch is equal to 89.6%, 92.6%, and 82.2% using Gaussian RBF, polynomial and linear functions, respectively. These studies reveal the polynomial function has a better performance compared to the other kernel functions.

VI. COMPARISON OF DIFFERENT METHODS

Various features and performance evaluation indices of different types of IDSs are compared with each other as presented in Table 8. In this table, very fast, fast and medium refer to "less than 40 ms", "less than 200ms" and "less than 1s", respectively. Moreover, high implementation cost means that those IDS methods require new devices to be installed in the SGBMG. Moderate cost means they do not require additional devices while they may need some hardware improvement and minor changes in the islanding detection relays. In addition, low cost methods can be implemented using the existing devices without any additional expenditures.

As presented in this table, communication-based (remote) and active methods have proper performance in fast detecting of the islanding events even with zero power mismatch. However, these techniques may not be always applicable due to their high cost as well as implementation complexities. In addition, active methods may have adverse impacts on the SGBMGs transient stability and steady-state operation. Considering these facts, local passive methods are mostly recommended for the SGBMGs.

Conventional widely-used passive methods have a large NDZ region and low detection speed. Furthermore, the amount of threshold values has significant impact on the performance of these methods which is a negative feature. Therefore, proper adjustment of these threshold parameters enhances the conventional methods performance. Using proper monitoring indices can improve the IDS speed and reduce the amount of NDZ. However, using these indices cannot completely eliminate the NDZ region. It is highly recommended to employ adaptive thresholds to enhance the security of these indices against non-islanding events and decrease their dependency on the predefined thresholds. Feature extraction based on signal processing techniques and intelligent methods can significantly decrease the amount of

TABLE 8. Comparison of various islanding detection algorithms.

Method		Adverse impact on steady-state operation	NDZ	Speed	FDR	Cost	Network configuration dependency	Threshold dependency	Training data dependency	Computation burden
Communication-based (Remote)		No	Zero	Very fast	Low	High	High	Low	None	Low
Active (Local)		Yes	Zero	Fast	Moderate	High	Moderate	Moderate	None	Low
Passive (Local)	Conventional	No	High	Medium	High	Low	Moderate	High	None	Low
	Using proper setting rules	No	Moderate	Medium	Moderate	Low	Moderate	High	None	Low
	Monitoring proper indices	No	Low	Fast	Moderate	Low	Moderate	Moderate	None	Low
	Monitoring proper indices and using adaptive thresholds	No	Low	Fast	Low	Low	Low	Low	None	Moderate
	Feature extraction and signal processing	No	Almost zero	Very fast	Low	Medium	Low	Moderate	None	High
	Intelligent techniques	No	Almost zero	Very fast	Low	Medium	Moderate	Low	High	High

NDZ. Moreover, these methods can improve the detection speed and IDS security. The main drawback of data mining methods is their high dependency on the training data and system configuration. Therefore, they are not recommended for practical applications in which the feeder configuration changes frequently. Moreover, both of the signal processing-based methods and intelligent techniques suffer from high computation burden and they require more powerful hardware and processors compared to the other passive methods. Based on these comparison results and our industrial experiences, utilizing proper indices along with proper signal processing technique methods and using adaptive thresholds would be the most suitable scheme for SGBMGs.

VII. NEW IDEAS FOR THE FUTURE WORKS

Based on the extensive investigations of the existing research works performed in this paper and the industrial experiences of the authors, the following recommendations are suggested for further research works and to improve the performance of the existing techniques.

A. INTEGRATED CENTRAL ISLANDING DETECTION FUNCTION

An SGBMG may contain multiple SSSGs with various control modes. In this case, it is recommended to integrate the islanding detection function of the SSSGs and use a central islanding detection unit for the whole SGBMG. To do so, the data of all SSSGs and their associated transformers should be utilized to achieve the best performance.

B. USING ADAPTIVE THRESHOLDS

Using adaptive thresholds is recently recommended by a few research works which can effectively improve the IDS security against non-islanding events and also reduce the NDZ region. The following factors are suggested to be considered in the calculation of the adaptive thresholds:

- SSSG active/reactive power control mode (e.g., constant power and droop);
- System configuration (e.g., feeder configuration, status of the other SSSGs, status of the large loads and etc.);
- Dynamic behavior of the system loads using their aggregated model;
- Active/reactive power passing through the PCC;
- SGBMG total inertia (including induction motors and the SSSGs);
- Amount of load sharing between the SSSGs.

C. UTILIZING NEUTRAL CURRENT

A very high percentage of the short circuit faults include the ground, i.e. single phase and double phase to ground faults. One of the effective signals which can be employed to discriminate islanding events from fault conditions is the zero-sequence current and its associated harmonics. There are various methods to recognize the zero-sequence signal including the summation of the measured phase signals or using a suitable separate current transformer (CT), e.g. core balance CT or neutral point CT. The summation method has a large amount of error during various conditions (e.g. motor starting, cold load pickup, fault and etc.), and thus, it is not recommended for islanding detection purposes. To provide acceptable performance, it is suggested to measure this signal directly through the grounded neutral of the SSSG step-up transformer.

The SSSGs are commonly connected to the upstream system through a step-up YNd transformer and the transformer neutral current is directly measured by a single phase neutral current transformer (NCT). The NCT output can be employed to discriminate islanding conditions from other events especially ground faults.

D. USING THE CURRENT NEGATIVE SEQUENCE

As expressed in section II, the islanding condition may unsymmetrically occur due to the open circuit condition in one phase. This condition may result in damage to SSSG and other equipment and thus, should be detected as fast as possible to perform the proper control and protection actions. The ratio of negative sequence of the current signal to its positive sequence (I_2/I_1) and also its rate of change can be effectively employed to detect such a condition.

E. COMBINED APPLICATION OF SIGNAL PROCESSING APPROACHES

Each signal processing method may have some advantages and disadvantageous due to the type of the occurred transient. Therefore, it is suggested to utilize a combination of the signal processing approaches and fuse their output decision to increase the detection performance for different transient types and minimize the FDR and NDZ.

VIII. CONCLUSION

The islanding condition of MGs should be detected as fast as possible to perform proper control actions and prevent possible adverse effects on the upstream system. In this paper, a comprehensive technical review of islanding detection techniques of SGBMGs is offered. At first, several suitable indices have been introduced which can be practically employed to evaluate the performance of the IDSs and select the most appropriate one for an SGBMG. Then, various IDSs applicable to SGBMGs are investigated and compared carefully. Each of the presented methods may be suitable for some SGBMGs and thus, the most compatible IDS for a specific SGBMG should be selected based on the obtained comparison results. Based on the investigations, the islanding condition of SGBMGs can be sensibly detected using passive methods even under zero power mismatch conditions and without requiring any intentional perturbations. Meanwhile, active methods are not recommended for SGBMGs. The investigations of this paper reveal that the most viable passive method is monitoring the proper islanding detection indices along with using feature extracting techniques which can significantly reduce the SGBMG NDZ region. Moreover, the performance of these passive methods can be further improved by using intelligent techniques which mainly operate based on the data-mining techniques. In addition, employing adaptive thresholds enhances the IDS security against non-islanding events and also decreases the IDS dependency on the network configuration. Additionally, several practical and useful recommendations and suggestions have been presented in this paper for future research works and further improvements of the existing passive methods.

REFERENCES

[1] Z. Li, M. Shahidehpour, F. Aminifar, A. Alabdulwahab, and Y. Al-Turki, "Networked microgrids for enhancing the power system resilience," *Proc. IEEE*, vol. 105, no. 7, pp. 1289–1310, Jul. 2017.
[2] M. N. Alam, S. Chakrabarti, and A. Ghosh, "Networked microgrids: State-of-the-art and future perspectives," *IEEE Trans. Ind. Informat.*, vol. 15, no. 3, pp. 1238–1250, Mar. 2018.
[3] J. Yang, A. Paudel, and H. B. Gooi, "Compensation for power loss by a proof-of-stake consortium blockchain microgrid," *IEEE Trans. Ind. Informat.*, vol. 17, no. 5, pp. 3253–3262, May 2021.
[4] W. El-Khattam and M. M. A. Salama, "Distributed generation technologies, definitions and benefits," *Electr. Power Syst. Res.*, vol. 71, no. 2, pp. 119–128, Oct. 2004.
[5] Zaheeruddin and M. Manas, "Analysis of design of technologies, tariff structures, and regulatory policies for sustainable growth of the smart grid," *Energy Technol. Policy*, vol. 2, no. 1, pp. 28–38, Jan. 2015.
[6] M. Baneshi and F. Hadianfard, "Techno-economic feasibility of hybrid diesel/PV/wind/battery electricity generation systems for non-residential large electricity consumers under southern Iran climate conditions," *Energy Convers. Manage.*, vol. 127, pp. 233–244, Nov. 2016.
[7] S. Bahramara, M. Yazdani-Damavandi, J. Contreras, M. Shafie-Khah, and J. P. S. Catalão, "Modeling the strategic behavior of a distribution company in wholesale energy and reserve markets," *IEEE Trans. Smart Grid*, vol. 9, no. 4, pp. 3857–3870, Jul. 2018.
[8] F. Katiraei, M. R. Iravani, and P. W. Lehn, "Micro-grid autonomous operation during and subsequent to islanding process," *IEEE Trans. Power Del.*, vol. 20, no. 1, pp. 248–257, Jan. 2005.
[9] *IEEE Standard for Interconnection and Interoperability of Distributed Energy Resources With Associated Electric Power Systems Interfaces*, Standard 1547-2018 (Revision of IEEE Std 1547-2003), IEEE, 2018.
[10] Y. Vilaisarn, M. Moradzadeh, M. Abdelaziz, and J. Cros, "An MILP formulation for the optimum operation of AC microgrids with hierarchical control," *Int. J. Electr. Power Energy Syst.*, vol. 137, May 2022, Art. no. 107674.
[11] A. L. Finkler, J. M. Lenz, A. Sausen, M. D. Campos, and P. S. Sausen, "Challenges on the use of vector shift relays in distributed generation: A Brazilian case study," *Electr. Power Syst. Res.*, vol. 204, Mar. 2022, Art. no. 107688.
[12] K. Naraghipour, I. Abdelsalam, K. H. Ahmed, and C. D. Booth, "Modified Q–f droop curve method for islanding detection with zero non-detection zone," *IEEE Access*, vol. 9, pp. 158027–158040, 2021.
[13] N. K. Swarnkar, O. P. Mahela, B. Khan, and M. Lalwani, "Identification of islanding events in utility grid with renewable energy penetration using current based passive method," *IEEE Access*, vol. 9, pp. 93781–93794, 2021.
[14] K. Jia, H. Wei, T. Bi, D. W. P. Thomas, and M. Sumner, "An islanding detection method for multi-DG systems based on high-frequency impedance estimation," *IEEE Trans. Sustain. Energy*, vol. 8, no. 1, pp. 74–83, Jan. 2017.
[15] M. R. Alam, M. T. A. Begum, and K. M. Muttaqi, "Assessing the performance of ROCOF relay for anti-islanding protection of distributed generation under subcritical region of power imbalance," *IEEE Trans. Ind. Appl.*, vol. 55, no. 5, pp. 5395–5405, Sep. 2019.
[16] M. Mishra, S. Chandak, and P. K. Rout, "Taxonomy of islanding detection techniques for distributed generation in microgrid," *Renew. Energy Focus*, vol. 31, pp. 9–30, Dec. 2019.

[17] J. C. M. Vieira, W. Freitas, W. Xu, and A. Morelato, "An investigation on the nondetection zones of synchronous distributed generation anti-islanding protection," *IEEE Trans. Power Del.*, vol. 23, no. 2, pp. 593–600, Apr. 2008.

[18] H. Abdi, A. Rostami, and N. Rezaei, "A novel passive islanding detection scheme for synchronous-type DG using load angle and mechanical power parameters," *Electr. Power Syst. Res.*, vol. 192, Mar. 2021, Art. no. 106968.

[19] A. K. Özcanlı and M. Baysal, "A novel multi-LSTM based deep learning method for islanding detection in the microgrid," *Electr. Power Syst. Res.*, vol. 202, Jan. 2022, Art. no. 107574.

[20] D. Salles, W. Freitas, J. C. M. Vieira, and B. Venkatesh, "A practical method for nondetection zone estimation of passive anti-islanding schemes applied to synchronous distributed generators," *IEEE Trans. Power Del.*, vol. 30, no. 5, pp. 2066–2076, Oct. 2015.

[21] Y. Li, P. Zhang, J. N. Debs, D. A. Ferrante, D. J. Kane, S. N. Woolard, R. S. Kalbfleisch, and K. B. Bowes, "A generic method for the determination of non-detection zones in DER-dominated distribution grids," in *Proc. IEEE Power Energy Soc. Gen. Meeting (PESGM)*, Aug. 2018, pp. 1–5.

[22] Y. Li, P. Zhang, W. Li, J. N. Debs, D. A. Ferrante, D. J. Kane, S. N. Woolard, R. Kalbfleisch, K. B. Bowes, and A. J. Kasznay, "Non-detection zone analytics for unintentional islanding in a distribution grid integrated with distributed energy resources," *IEEE Trans. Sustain. Energy*, vol. 10, no. 1, pp. 214–225, Jan. 2019.

[23] Z. Ye, A. Kolwalkar, Y. Zhang, P. Du, and R. Walling, "Evaluation of anti-islanding schemes based on nondetection zone concept," *IEEE Trans. Power Electron.*, vol. 19, no. 5, pp. 1171–1176, Sep. 2004.

[24] R. Bekhradian, M. Davarpanah, and M. Sanaye-Pasand, "Novel approach for secure islanding detection in synchronous generator based microgrids," *IEEE Trans. Power Del.*, vol. 34, no. 2, pp. 457–466, Apr. 2019.

[25] W. Zheng, P. Crossley, B. Xu, and H. Qi, "Transient stability of a distribution subsystem during fault-initiated switching to islanded operation," *Int. J. Electr. Power Energy Syst.*, vol. 97, pp. 418–427, Apr. 2018.

[26] A. Pouryekta, V. K. Ramachandaramurthy, N. Mithulananthan, and A. Arulampalam, "Islanding detection and enhancement of microgrid performance," *IEEE Syst. J.*, vol. 12, no. 4, pp. 3131–3141, Dec. 2018.

[27] R. Zamani, M. P. Moghaddam, H. Panahi, and M. Sanaye-Pasand, "Fast islanding detection of nested grids including multiple resources based on phase criteria," *IEEE Trans. Smart Grid*, vol. 12, no. 6, pp. 4962–4970, Nov. 2021.

[28] M. W. Altaf, M. T. Arif, S. Saha, S. N. Islam, M. E. Haque, and A. M. T. Oo, "Effective ROCOF-based islanding detection technique for different types of microgrid," *IEEE Trans. Ind. Appl.*, vol. 58, no. 2, pp. 1809–1821, Mar. 2022.

[29] A. Rostami, H. Abdi, M. Moradi, J. Olamaei, and E. Naderi, "Islanding detection based on ROCOV and ROCORP parameters in the presence of synchronous DG applying the capacitor connection strategy," *Electr. Power Compon. Syst.*, vol. 45, no. 3, pp. 315–330, Feb. 2017.

[30] S. Raza, H. Mokhlis, H. Arof, K. Naidu, J. A. Laghari, and A. S. M. Khairuddin, "Minimum-features-based ANN-PSO approach for islanding detection in distribution system," *IET Renew. Power Gener.*, vol. 10, no. 9, pp. 1255–1263, Oct. 2016.

[31] R. Bekhradian, M. Davarpanah, and M. Sanaye-Pasand, "Current-based blocking scheme to stabilize distribution network relays against FIDVR," *Int. J. Electr. Power Energy Syst.*, vol. 132, Nov. 2021, Art. no. 107205.

[32] M. A. Ebrahim, F. Wadie, and M. A. Abd-Allah, "An algorithm for detection of fault, islanding, and power swings in DG-equipped radial distribution networks," *IEEE Syst. J.*, vol. 14, no. 3, pp. 3893–3903, Sep. 2020.

[33] A. H. K. Alaboudy, H. H. Zeineldin, and J. Kirtley, "Microgrid stability characterization subsequent to fault-triggered islanding incidents," *IEEE Trans. Power Del.*, vol. 27, no. 2, pp. 658–669, Apr. 2012.

[34] D. Salles, W. Freitas, J. C. M. Vieira, and W. Xu, "Nondetection index of anti-islanding passive protection of synchronous distributed generators," *IEEE Trans. Power Del.*, vol. 27, no. 3, pp. 1509–1518, Jul. 2012.

[35] A. Mazloomzadeh, M. H. Cintuglu, and O. A. Mohammed, "Islanding detection using synchronized measurement in smart microgrids," in *Proc. IEEE PES Conf. Innov. Smart Grid Technol. (ISGT Latin America)*, Apr. 2013, pp. 1–7.

[36] M. M. Ostojić and M. B. Djurić, "The algorithm with synchronized voltage inputs for islanding detection of synchronous generators," *Int. J. Electr. Power Energy Syst.*, vol. 103, pp. 431–439, Dec. 2018.

[37] W. Xu, G. Zhang, C. Li, W. Wang, G. Wang, and J. Kliber, "A power line signaling based technique for anti-islanding protection of distributed generators—Part I: Scheme and analysis," *IEEE Trans. Power Del.*, vol. 22, no. 3, pp. 1758–1766, Jul. 2007.

[38] W. Wang, J. Kliber, G. Zhang, W. Xu, B. Howell, and T. Palladino, "A power line signaling based scheme for anti-islanding protection of distributed generators—Part II: Field test results," *IEEE Trans. Power Del.*, vol. 22, no. 3, pp. 1767–1772, Jul. 2007.

[39] W. Wang, J. Kliber, and W. Xu, "A scalable power-line-signaling-based scheme for islanding detection of distributed generators," *IEEE Trans. Power Del.*, vol. 24, no. 2, pp. 903–909, Apr. 2009.

[40] A. Khamis, H. Shareef, E. Bizkevelci, and T. Khatib, "A review of islanding detection techniques for renewable distributed generation systems," *Renew. Sustain. Energy Rev.*, vol. 28, pp. 483–493, Dec. 2013.

[41] W. Bower and M. Ropp, "Evaluation of islanding detection methods for photovoltaic utility interactive power systems," Int. Energy Agency (IEA), Sandia Nat. Lab., Albuquerque, NM, USA, Tech. Rep. IEA-PVPS T5-09, 2002.

[42] C. Li, C. Cao, Y. Cao, Y. Kuang, L. Zeng, and B. Fang, "A review of islanding detection methods for microgrid," *Renew. Sustain. Energy Rev.*, vol. 35, pp. 211–220, Jul. 2014.

[43] H. Laaksonen, "Advanced islanding detection functionality for future electricity distribution networks," *IEEE Trans. Power Del.*, vol. 28, no. 4, pp. 2056–2064, Oct. 2013.

[44] G. P. Kumar and P. Jena, "Pearson's correlation coefficient for islanding detection using micro-PMU measurements," *IEEE Syst. J.*, vol. 15, no. 4, pp. 5078–5089, Dec. 2021.

[45] B. Dob and C. Palmer, "Communications assisted islanding detection: Contrasting direct transfer trip and phase comparison methods," in *Proc. 71st Annu. Conf. Protective Relay Eng. (CPRE)*, Mar. 2018, pp. 1–6.

[46] F. Coffele, P. Moore, C. Booth, A. Dysko, G. Burt, T. Spearing, and P. Dolan, "Centralized loss of mains protection using IEC-61850," in *Proc. 10th IET Int. Conf. Develop. Power Syst. Protection (DPSP)*, Mar. 2010, pp. 1–5.

[47] A. Timbus, A. Oudalov, and C. N. M. Ho, "Islanding detection in smart grids," in *Proc. IEEE Energy Convers. Congr. Expos.*, Sep. 2010, pp. 3631–3637.

[48] A. Rostami, A. Jalilian, M. T. Hagh, K. M. Muttaqi, and J. Olamaei, "Islanding detection of distributed generation based on rate of change of exciter voltage with circuit breaker switching strategy," *IEEE Trans. Ind. Appl.*, vol. 55, no. 1, pp. 954–963, Jan. 2019.

[49] D. Bejmert and T. S. Sidhu, "Investigation into islanding detection with capacitor insertion-based method," *IEEE Trans. Power Del.*, vol. 29, no. 6, pp. 2485–2492, Dec. 2014.

[50] R. Zamani, M. E. H. Golshan, H. H. Alhelou, and N. Hatziargyriou, "A novel hybrid islanding detection method using dynamic characteristics of synchronous generator and signal processing technique," *Electr. Power Syst. Res.*, vol. 175, Oct. 2019, Art. no. 105911.

[51] J. A. Laghari, H. Mokhlis, A. H. A. Bakar, and M. Karimi, "A new islanding detection technique for multiple mini hydro based on rate of change of reactive power and load connecting strategy," *Energy Convers. Manage.*, vol. 76, pp. 215–224, Dec. 2013.

[52] G. Marchesan, M. R. Muraro, G. Cardoso, L. Mariotto, and A. P. de Morais, "Passive method for distributed-generation island detection based on oscillation frequency," *IEEE Trans. Power Del.*, vol. 31, no. 1, pp. 138–146, Feb. 2016.

[53] J. C. M. Vieira, D. S. Correa, W. Freitas, and W. Xu, "Performance curves of voltage relays for islanding detection of distributed generators," *IEEE Trans. Power Syst.*, vol. 20, no. 3, pp. 1660–1662, Aug. 2005.

[54] B. Liu, D. Thomas, K. Jia, and M. Woolfson, "Advanced ROCOF protection of synchronous generator," in *Proc. ISGT*, 2011, pp. 1–6.

[55] K. El-Arroudi and G. Joos, "Data mining approach to threshold settings of islanding relays in distributed generation," *IEEE Trans. Power Syst.*, vol. 22, no. 3, pp. 1112–1119, Aug. 2007.

[56] J. C. M. Vieira, D. Salles, and W. Freitas, "Power imbalance application region method for distributed synchronous generator anti-islanding protection design and evaluation," *Electr. Power Syst. Res.*, vol. 81, no. 10, pp. 1952–1960, Oct. 2011.

[57] X. Xie, C. Huang, and D. Li, "A new passive islanding detection approach considering the dynamic behavior of load in microgrid," *Int. J. Electr. Power Energy Syst.*, vol. 117, May 2020, Art. no. 105619.

[58] X. Xie, W. Xu, C. Huang, and X. Fan, "New islanding detection method with adaptively threshold for microgrid," *Electr. Power Syst. Res.*, vol. 195, Jun. 2021, Art. no. 107167.

[59] S. Raza, H. Mokhlis, H. Arof, J. A. Laghari, and H. Mohamad, "A sensitivity analysis of different power system parameters on islanding detection," *IEEE Trans. Sustain. Energy*, vol. 7, no. 2, pp. 461–470, Apr. 2016.

[60] A. R. Di Fazio, G. Fusco, M. Russo, S. Valeri, C. Noce, and G. Amura, "A smart device for islanding detection in distribution system operation," *Electr. Power Syst. Res.*, vol. 120, pp. 87–95, Mar. 2015.

[61] P. Kumar, V. Kumar, and B. Tyagi, "A novel islanding detection technique based on event index value for reconfigurable microgrid," *IEEE Trans. Ind. Appl.*, vol. 57, no. 4, pp. 3451–3462, Jul. 2021.

[62] S. Nikolovski, H. R. Baghaee, and D. Mlakic, "Islanding detection of synchronous generator-based DGs using reactive power rate of change," *IEEE Syst. J.*, vol. 13, no. 4, pp. 1–11, Dec. 2019.

[63] G. Marchesan, K. Maresch, G. Cardoso, A. P. de Morais, and M. R. Muraro, "Distributed synchronous generation ride-through enhancement by anti-islanding protection blocking," *Electr. Power Syst. Res.*, vol. 196, Jul. 2021, Art. no. 107232.

[64] H. Muda and P. Jena, "Phase angle-based PC technique for islanding detection of distributed generations," *IET Renew. Power Gener.*, vol. 12, no. 6, pp. 735–746, Apr. 2018.

[65] K. Sareen, B. R. Bhalja, and R. P. Maheshwari, "Universal islanding detection technique based on rate of change of sequence components of currents for distributed generations," *IET Renew. Power Gener.*, vol. 10, no. 2, pp. 228–237, 2016.

[66] S. Raza, H. Arof, H. Mokhlis, H. Mohamad, and H. A. Illias, "Passive islanding detection technique for synchronous generators based on performance ranking of different passive parameters," *IET Gener., Transmiss. Distrib.*, vol. 11, no. 17, pp. 4175–4183, Nov. 2017.

[67] J. A. Laghari, H. Mokhlis, M. Karimi, A. H. A. Bakar, and H. Mohamad, "An islanding detection strategy for distribution network connected with hybrid DG resources," *Renew. Sustain. Energy Rev.*, vol. 45, pp. 662–676, May 2015.

[68] S. Raza, H. Mokhlis, H. Arof, J. A. Laghari, and L. Wang, "Application of signal processing techniques for islanding detection of distributed generation in distribution network: A review," *Energy Convers. Manage.*, vol. 96, pp. 613–624, May 2015.

[69] Y. M. Makwana and B. R. Bhalja, "Experimental performance of an islanding detection scheme based on modal components," *IEEE Trans. Smart Grid*, vol. 10, no. 1, pp. 1025–1035, Jan. 2019.

[70] B. K. Chaitanya, A. Yadav, and M. Pazoki, "An advanced signal decomposition technique for islanding detection in DG system," *IEEE Syst. J.*, vol. 15, no. 3, pp. 3220–3229, Sep. 2021.

[71] R. Zamani, M. E. H. Golshan, H. H. Alhelou, and N. Hatziargyriou, "A novel synchronous DGs islanding detection method based on online dynamic features extraction," *Electr. Power Syst. Res.*, vol. 195, Jun. 2021, Art. no. 107180.

[72] M. Bakhshi, R. Noroozian, and G. B. Gharehpetian, "Anti-islanding scheme for synchronous DG units based on Tufts–Kumaresan signal estimation method," *IEEE Trans. Power Del.*, vol. 28, no. 4, pp. 2185–2193, Oct. 2013.

[73] A. Samui and S. R. Samantaray, "Wavelet singular entropy-based islanding detection in distributed generation," *IEEE Trans. Power Del.*, vol. 28, no. 1, pp. 411–418, Jan. 2012.

[74] R. Dubey, M. Popov, and S. R. Samantaray, "Transient monitoring function-based islanding detection in power distribution network," *IET Gener., Transmiss. Distrib.*, vol. 13, no. 6, pp. 805–813, Mar. 2019.

[75] M. A. Farhan and K. S. Swarup, "Mathematical morphology-based islanding detection for distributed generation," *IET Gener., Transmiss. Distrib.*, vol. 11, no. 14, pp. 3449–3457, Sep. 2017.

[76] R. Nale, M. Biswal, and N. Kishor, "A transient component based approach for islanding detection in distributed generation," *IEEE Trans. Sustain. Energy*, vol. 10, no. 3, pp. 1129–1138, Jul. 2019.

[77] C.-T. Hsieh, J.-M. Lin, and S.-J. Huang, "Enhancement of islanding-detection of distributed generation systems via wavelet transform-based approaches," *Int. J. Electr. Power Energy Syst.*, vol. 30, no. 10, pp. 575–580, Dec. 2008.

[78] B. K. Chaitanya and A. Yadav, "Hilbert–Huang transform based islanding detection scheme for distributed generation," in *Proc. IEEE 8th Power India Int. Conf. (PIICON)*, Dec. 2018, pp. 1–5.

[79] A. Ezzat, B. E. Elnaghi, and A. A. Abdelsalam, "Microgrids islanding detection using Fourier transform and machine learning algorithm," *Electr. Power Syst. Res.*, vol. 196, Jul. 2021, Art. no. 107224.

[80] C. Zhao, M. He, and X. Zhao, "Analysis of transient waveform based on combined short time Fourier transform and wavelet transform," in *Proc. Int. Conf. Power Syst. Technol. (PowerCon)*, Nov. 2004, pp. 1122–1126.

[81] S. R. Mohanty, N. Kishor, P. K. Ray, and J. P. S. Catalo, "Comparative study of advanced signal processing techniques for islanding detection in a hybrid distributed generation system," *IEEE Trans. Sustain. Energy*, vol. 6, no. 1, pp. 122–131, Jan. 2015.

[82] P. K. Ray, N. Kishor, and S. R. Mohanty, "Islanding and power quality disturbance detection in grid-connected hybrid power system using wavelet and S-transform," *IEEE Trans. Smart Grid*, vol. 3, no. 3, pp. 1082–1094, Sep. 2012.

[83] P. K. Ray, S. R. Mohanty, and N. Kishor, "Disturbance detection in grid-connected distributed generation system using wavelet and S-transform," *Electr. Power Syst. Res.*, vol. 81, no. 3, pp. 805–819, Mar. 2011.

[84] M. Karimi, H. Mokhtari, and M. R. Iravani, "Wavelet based on-line disturbance detection for power quality applications," *IEEE Trans. Power Del.*, vol. 15, no. 4, pp. 1212–1220, Oct. 2000.

[85] P. K. Dash, B. K. Panigrahi, and G. Panda, "Power quality analysis using S-transform," *IEEE Trans. Power Del.*, vol. 18, no. 2, pp. 406–411, Apr. 2003.

[86] C. N. Bhende, S. Mishra, and B. K. Panigrahi, "Detection and classification of power quality disturbances using S-transform and modular neural network," *Electr. Power Syst. Res.*, vol. 78, no. 1, pp. 122–128, Jan. 2008.

[87] H. S. Behera, P. K. Dash, and B. Biswal, "Power quality time series data mining using S-transform and fuzzy expert system," *Appl. Soft Comput.*, vol. 10, no. 3, pp. 945–955, Jun. 2010.

[88] S. Ventosa, C. Simon, M. Schimmel, J. J. Danobeitia, and A. Mànuel, "The S-transform from a wavelet point of view," *IEEE Trans. Signal Process.*, vol. 56, no. 7, pp. 2771–2780, Jul. 2008.

[89] S. R. Mohanty, N. Kishor, P. K. Ray, and J. P. S. Catalao, "Islanding detection in a distributed generation based hybrid system using intelligent pattern recognition techniques," in *Proc. 3rd IEEE PES Innov. Smart Grid Technol. Eur. (ISGT Europe)*, Oct. 2012, pp. 1–5.

[90] S. Agrawal, S. Patra, S. R. Mohanty, V. Agarwal, and M. Basu, "Use of matrix-pencil method for efficient islanding detection in static DG and a parallel comparison with DWT method," *IEEE Trans. Ind. Electron.*, vol. 66, no. 11, pp. 8937–8946, Nov. 2019.

[91] H. Li, Z. Li, and W. Mo, "A time varying filter approach for empirical mode decomposition," *Signal Process.*, vol. 138, pp. 146–158, Sep. 2017.

[92] C. Simon, M. Schimmel, and J. J. Danobeitia, "On the TT-transform and its diagonal elements," *IEEE Trans. Signal Process.*, vol. 56, no. 11, pp. 5709–5713, Nov. 2008.

[93] S. Suja and J. Jerome, "Pattern recognition of power signal disturbances using S-transform and TT-transform," *Int. J. Electr. Power Energy Syst.*, vol. 32, no. 1, pp. 37–53, Jan. 2010.

[94] C. R. Pinnegar, "Time–frequency and time–time filtering with the S-transform and TT-transform," *Digit. Signal Process.*, vol. 15, no. 6, pp. 604–620, Nov. 2005.

[95] M. Jing, W. Zengping, X. Yan, and M. Lei, "Single-ended transient positional protection of transmission lines using mathematical morphology," in *Proc. Int. Power Eng. Conf.*, Nov. 2005, p. 603.

[96] P. Li, J. Liu, X. Li, C. Tian, and J. Jie, "Detection of power quality disturbances in microgrid based on generalized morphological filter and backward difference," in *Proc. 4th Int. Conf. Electr. Utility Deregulation Restructuring Power Technol. (DRPT)*, Jul. 2011, pp. 1663–1666.

[97] S. Gautam and S. M. Brahma, "Overview of mathematical morphology in power systems—A tutorial approach," in *Proc. IEEE Power Energy Soc. Gen. Meeting*, Jul. 2009, pp. 1–7.

[98] A. Hussain, C.-H. Kim, and A. Mehdi, "A comprehensive review of intelligent islanding schemes and feature selection techniques for distributed generation system," *IEEE Access*, vol. 9, pp. 146603–146624, 2021.

[99] S. Kar and S. R. Samantaray, "Data-mining-based intelligent anti-islanding protection relay for distributed generations," *IET Gener., Transmiss. Distrib.*, vol. 8, no. 4, pp. 629–639, Apr. 2014.

[100] S. R. Samantaray, K. El-Arroudi, G. Joos, and I. Kamwa, "A fuzzy rule-based approach for islanding detection in distributed generation," *IEEE Trans. Power Del.*, vol. 25, no. 3, pp. 1427–1433, Jul. 2010.

[101] O. N. Faqhruldin, E. F. El-Saadany, and H. H. Zeineldin, "A universal islanding detection technique for distributed generation using pattern recognition," *IEEE Trans. Smart Grid*, vol. 5, no. 4, pp. 1985–1992, Jul. 2014.

[102] B. K. Chaitanya, A. Yadav, and M. Pazoki, "Reliable islanding detection scheme for distributed generation based on pattern-recognition," *IEEE Trans. Ind. Informat.*, vol. 17, no. 8, pp. 5230–5238, Aug. 2021.

[103] A. Khamis, Y. Xu, Z. Y. Dong, and R. Zhang, "Faster detection of microgrid islanding events using an adaptive ensemble classifier," *IEEE Trans. Smart Grid*, vol. 9, no. 3, pp. 1889–1899, May 2018.

[104] K. El-Arroudi, G. Joos, I. Kamwa, and D. T. McGillis, "Intelligent-based approach to islanding detection in distributed generation," *IEEE Trans. Power Del.*, vol. 22, no. 2, pp. 828–835, Apr. 2007.

[105] S. Li, A. J. Rodolakis, K. El-Arroudi, and G. Joós, "Islanding protection of multiple distributed resources under adverse islanding conditions," *IET Gener., Transmiss. Distrib.*, vol. 10, no. 8, pp. 1901–1912, May 2016.

[106] M. Vatani, T. Amraee, A. M. Ranjbar, and B. Mozafari, "Relay logic for islanding detection in active distribution systems," *IET Gener., Transmiss. Distrib.*, vol. 9, no. 12, pp. 1254–1263, Sep. 2015.

[107] V. L. Merlin, R. C. Santos, A. P. Grilo, J. C. M. Vieira, D. V. Coury, and M. Oleskovicz, "A new artificial neural network based method for islanding detection of distributed generators," *Int. J. Elect. Power Energy Syst.*, vol. 75, pp. 139–151, Feb. 2016.

[108] H. Shayeghi, B. Sobhani, E. Shahryari, and A. Akbarimajd, "Optimal neuro-fuzzy based islanding detection method for distributed generation," *Neurocomputing*, vol. 177, pp. 478–488, Feb. 2016.

[109] S. R. Mohanty, P. K. Ray, N. Kishor, and B. Panigrahi, "Classification of disturbances in hybrid DG system using modular PNN and SVM," *Int. J. Elect. Power Energy Syst.*, vol. 44, no. 1, pp. 764–777, 2013.

[110] M. R. Alam, K. M. Muttaqi, and A. Bouzerdoum, "A multifeature-based approach for islanding detection of DG in the subcritical region of vector surge relays," *IEEE Trans. Power Del.*, vol. 29, no. 5, pp. 2349–2358, Oct. 2014.

REZA BEKHRADIAN received the B.Sc. degree in electrical engineering from the Amirkabir University of Technology, Tehran, Iran, in 2013, and the M.Sc. and Ph.D. degrees in electrical engineering from the University of Tehran, Tehran, in 2015 and 2021, respectively. His research interests include protection and control of microgrids and power systems.

MAJID SANAYE-PASAND (Senior Member, IEEE) received the B.Sc. degree in electrical engineering from the University of Tehran, Tehran, Iran, in 1988, and the M.Sc. and Ph.D. degrees in electrical engineering from the University of Calgary, Calgary, AB, Canada, in 1994 and 1998, respectively. He is currently a Professor with the School of Electrical and Computer Engineering, University of Tehran. His research interests include power system protection, control, and transients. He is also an Associate Editor of IEEE TRANSACTIONS ON SMART GRID and IEEE TRANSACTIONS ON POWER DELIVERY.

• • •