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A Comprehensive Review of Islanding Detection Methods for Both AC and DC Microgrids

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***Abstract*—Modernizing grid connectivity laws is necessary for the electric power systems' rapid proliferation of distributed generators (DGs), especially as microgrids (MGs) proliferate and speed up the decentralization of networks. Therefore, the rapid detection of unintentional islanding is much more necessary either for DGs operating in grid-connected mode or for MGs which have reliability for getting transition into Islanded mode. An overview of approaches for detecting and preventing islands in power systems is provided in this work. The two main categories for detecting islanding conditions for a distributed generation (DG) distribution system are classical and modern methods. For utility-side islanding detection, a modern technique is used, but for DG-side islanding detection, a classical technique is used. There are three other categories of classical techniques: hybrid, active, and passive. These methods for DG islanding detection are described and examined.**

***Index Terms*— AC Microgrid, DC Microgrid, Islanding Detection Techniques, NDZ, Distributed Generation.**

I. INTRODUCTION

Today's power generation system runs on the coordinated functioning of massive power plants that generate significant amounts of power and transmit that power over lengthy transmission lines at a high voltage before lowering the voltage for consumption inside client premises [1]. This is mostly caused by the fact that it is far less expensive to produce large amounts of electricity than several tiny amounts. However, the development of technologies such as fuel cells, gas turbines, micro-hydro, wind turbines, and photovoltaics, as well as new developments in power electronics and the deregulation of the electricity market as well as consumer demands for better power quality, reliability, and most importantly environmental concerns are forcing the power industry to make yet another shift this time back to distributed and dispersed generation [2].

An alternative central generating station, distributed or dispersed generation refers to generating resources that are located close to the load they are serving, typically at the client site. As DG can reduce transmission and distribution line losses, eliminate transmission and distribution (T&D) capacity improvements, enhance power quality, alter the voltage profile of the system, etc., their use in distribution systems is expanding [3]. The penetration of DG in various utility systems across the world is actually rather high. The DG, however, has a number of challenges, islanding being one of the most significant [4].

A scenario known as islanding occurs when a portion of the system that contains load and generation is cut off from the network. Moreover, islanding can be classified as either intentional or unintentional, with utilities being

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most concerned about the latter. In the above Figure.1 shows a straightforward for a local network when the grid was disconnected. Unintentional islanding could put utility line workers, members of the public, and distributed generators (DGs) in danger, particularly when the DG gets connected again because the utility has no control over the distributed generator (DG) and load [5]. Hence, efficient, safe, and trustworthy islanding detection techniques may be the key objectives for our growing future engineering purpose. In order to accomplish this, a DG must be outfitted with protection that will allow it to be disconnected from the load in the event that one or more network phases fail. This sort of protection, also known as loss of mains (LoMs) protection, is necessary to disconnect the DGs in order to prevent supplying customers with voltage and frequency that are outside of the permitted range [6]. The operation of AC and DC microgrids cannot be covered by the current IDMs thus they could not be completely compatible with how well the microgrids perform [7]. In this paper, there are six sections have been explored. To emphasize the aspects of islanding detection approaches, Section II discusses a number of international standards. The primary aspects of islanding situations are described in Section III. Section IV provides a thorough analysis of numerous IDMs classifications for inverter-based (single & multi) PVDG systems. Which IDM has adequate performance for AC MGs is examined in Section V. In Section VI, IDMs for DC microgrids have been described.

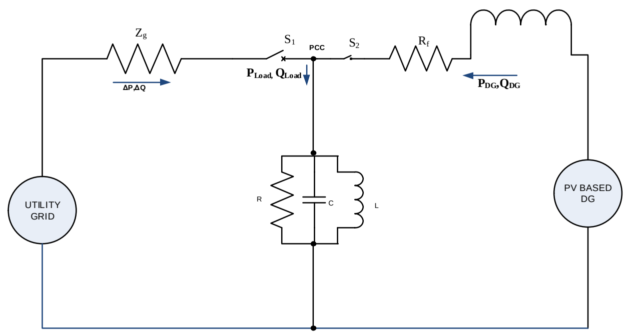

Figure 1: Islanding System with DG and Parallel RLC Circuit When the Grid is Disconnected

II. International Standardization for Islanding Condition

In general, most international standards have a similar fundamental concept of islanding detection methods for the PVDG grid-connected mode. They all take into account the same factors such as quality factor, voltage/frequency thresholds & detection time when they attempt to identify islands [8]. The number of the aforementioned criteria, however, may vary. Unfortunately, implementation using an expensive inverter is necessary because different standards have not been adjusted. So, inverter and PVDGs equipment expenses are more expensive than anticipated [9]. The primary criteria for several of the standards are presented in Table I.

Table I: International Standards Recommended for Anti-Islanding

S. NO.	**Standards**	**Frequency (Hz)**	**Quality Factor**	**Detection Time (sec)**	**Threshold Frequency (Hz)**	**Threshold Voltage (pu)**
1	IEEE 1547.1	60	1	≤ 2	59.29-60	0.879-1.1
2	IEEE 929	60	2.5	≤ 2	59.29-60	0.879-1.1
3	BS EN 50160	50	1	≤ 2	49-51	0.9-1.1
4	BS EN 62116	50	1	≤ 2	48.49-51.5	0.849-1.15

III. Primary Criteria and Parameters for Islanding Mode

To fulfil the international standards, performance indicators such as quality factor, frequency & voltage thresholds and detection time are taken into account. A general system was taken into consideration for the research of the IDT in accordance with IEEE 929, UL 1741, and IEEE 1547, as illustrated in Fig. 1 [10]. Parallel RLC networks are chosen as the load because they have a high-quality factor and low inductances, high capacitances, and high resistance [11]. The key formulas for evaluating islanding circumstances are shown below.

$$f_{res} = \frac{1}{2\Pi\sqrt{LC}} \quad (1)$$

$$Q_f = R\sqrt{\frac{C}{L}} \quad (2)$$

$$\left(\frac{V}{Vmax}\right)^2 - 1 \leq \frac{\Delta P}{P} \leq \left(\frac{V}{Vmin}\right)^2 - 1 \quad (3)$$

$$Q_f * \left(1 - \left(\frac{f}{fmin}\right)^2\right) \leq \frac{\Delta Q}{P} \leq Q_f * \left(1 - \left(\frac{f}{fmax}\right)^2\right) \quad (4)$$

Where f_{res} is the resonant frequency at (PCC) in Hz. R, L, C are the resistance (Ohm), Inductance (Henry) & Capacitance (Farad) respectively of a parallel RLC load and Q_f is the quality factor. In the same way V_{max}, $V_{min,}$ f_{max}, f_{min} are the permitted voltage and frequency ranges. In the above equation P is the rated active power of the PVDG system in Megawatt (MW). Also, $\Delta P = P_{Load} - P_{DG}$ and $\Delta Q = Q_{Load} - Q_{DG}$ are the active and reactive power mismatch during islanding events.

IV. Classification of Different Islanding Detection Techniques

There are several other IDMs that have been proposed in the literature, but none of them can simultaneously and economically satisfy all of the network's requirements [12]. As more power electronics-based DGs are used in single-based or multi-based inverter operation, the consensus for an IDM likewise deteriorates. On the other hand, since AC and DC microgrids are becoming more prevalent in the distribution network, their use with IDMs needs to be assessed and updated [1]. Therefore, Fig. 2 shows a revision to the IDM category. Only a small number of articles have examined the ID for operating microgrids, despite the fact that many have analysed IDMs [13]. The benefits and drawbacks of a wide variety of current inverter-based (single & multi) IDMs are reviewed in the sections that follow.

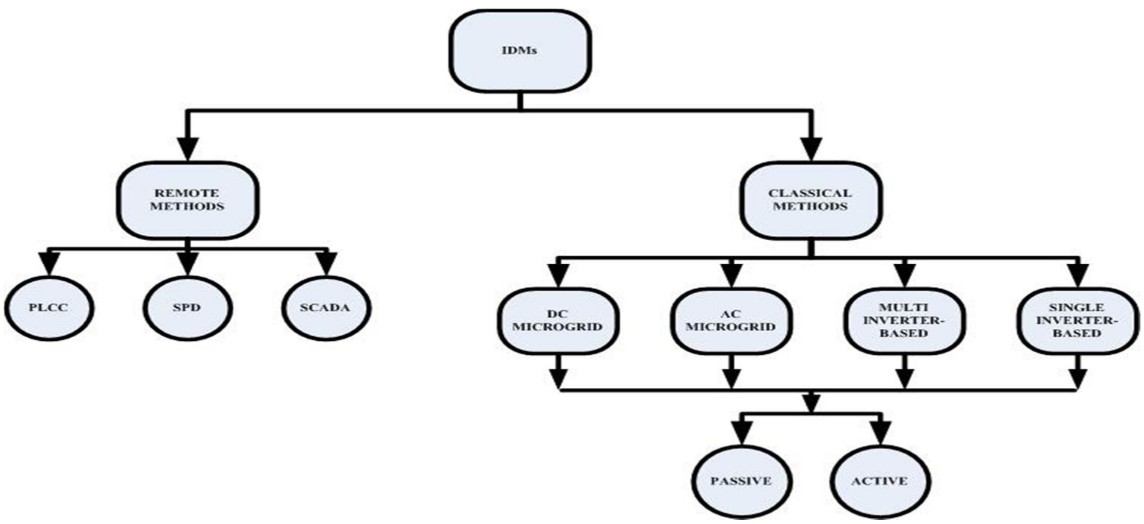

Figure 2: Classification of different IDMs

A. Classical Methods

The basis of conventional/classical islanding detection methods is typically the local voltage and current signals recorded at the point of common coupling (PCC) [14]. Passive and active approaches are the two sub-types that can be further separated. Numerous active and passive approaches are covered in the following sections.

Passive Method

The electrical characteristics monitored by passive detection methods at the PCC are voltage, current, frequency and harmonic distortion respectively. If the specified parameters measured at PCC exceeds the threshold value, then the islanding mode is detected otherwise, it is inside the non-detection zone (NDZ) [15]. In Figure 3, Table II which describes the typical passive traditional/classical methods with their benefits and demerits that are relevant for inverter-based (single & multi) distributed generation. Islanding detection has been accomplished using IDM approaches based on signal processing (SP). Since the passive islanding detection techniques do not degrade the power quality so, they compete with Active islanding detection techniques which have small NDZ. In Signal Processing (SP) techniques, choosing a threshold value is a challenging problem, especially when the preset number is big and the islanding cannot be detected. In Table III, Figure. 4 present the most typical of them for inverter-based distributed generation system whether they are Single or Multi.

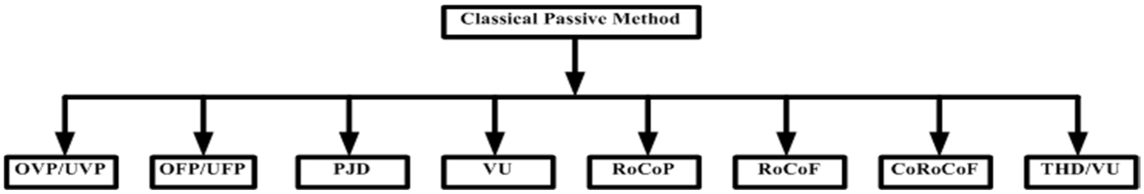

Figure 3: Classical Passive Methods

TABLE II: IDMs – IDMs OF CLASSICAL PASSIVE METHODS

S. No.	IDMs Name	Reference	Detection Time	Vivid	Advantage	Disadvantage
1.	Over/Under Voltage (OVP/UVP)	[1],[25],[26]	≤ 2 sec	$\Delta P \neq 0$ / $\Delta Q \neq 0$, $\Delta V \neq 0$	Simple and low cost	NDZ≠0
2.	Over/Under Frequency (OFP/UFP)	[1],[25],[26]	≤ 1 sec	$\Delta Q \neq 0$, $\Delta f \neq 0$	Simple and low cost	NDZ≠0
3.	Phase Jump Detection (PJD)	[26],[27]	≤ 2 sec	Depending on the PCC's voltage and current's phase difference	Simple and inexpensive, with little impact on power quality	NDZ≠0, Not applicable in LoMs
4.	Voltage Unbalance (VU)	[20],[28]	0.053 sec	Based on measurement of V-/V+	Simple and low cost	NDZ≠0, possibility of poor functioning
5.	Rate of change of power (RoCoP)	[9],[20]	0.1 sec	Compare 6f/6PLwith pre-set threshold	Simple and low cost	NDZ≠0
6.	Rate of change of frequency (RoCoF)	[16]	≤ 1 sec	According to measurement of df/dt	Easy and quick detection	Subject to the inertia of the system
7.	Comparison of RoCoF	[12]	0.6 sec	df/dt and DG's grid frequency should be compared.	capable of recognising grid disruption and LoMs	Its functioning possible with a significant frequency change
8.	Total harmonic distortion (THD)/VU	[27]	0.129 sec	Hybrid approach to quantify VU and THD	Easy and quick detection	When Q_f is higher, it fails

TABLE III: IDMs OF CLASSICAL NEW PASSIVE METHODS – SIGNAL PROCESSING AND INTELLIGENCE TECHNIQUES

S. No.	IDMs Name	Reference	Detection Time	Vivid	Advantage	Disadvantage
1.	Wavelet Transform (WT)	[9],[12]	≤ 0.6 sec	According to a tiny wavelet	Easy and quick detection	Under loud noise, unable to discern
2.	Fourier Transform (FT)	[13]	≤ 2 cycles	Utilising various frequency signals	Quick detection	Inability to eliminate transients
3.	S Transform (ST)	[12],[13]	≤ 0.03 sec	Based on a scalable and mobile Gaussian window	Rapidly detectable	Fails when there are brief interruptions
4.	Time-Time Transform (TTT)	[1],[9]	Predetermined period of time to compare the STD to the threshold	Similar to ST, but with a 2-D Time-Time signal as well	Rapidly detectable	Sensitive to noise
5.	Hilbert-Huang Transform (HHT)	[9],[13]	≤ 2 cycles	Used to handle non-stationary and non-linear signals	Easy and quick detection	Not suitable for all application
6.	Fuzzy Logic (FL)	[12]	≤ 1 cycle	Based on the use of a fuzzy classifier in data mining	NDZ=0.works with multi-inverter	Complexity and dimensionality of classification problem

7.	Artificial Neural Network based (ANN)	[20]	0.7 sec	Processed created using the brain's neural structure	Effective island detection	Longer computational times for training
8.	Decision Tree based (DT)	[12],[13]	0.045-0.050 sec	Combination of WPT & DWT	Fast detection	NDZ≠0
9.	Naïve Bayesian Classifier (NB)	[31]	NA	Based on Bayes' theorem	Simple, work with multi-inverter	NDZ≠0
10.	Support Vector Machine classifier (SVM)	[13],[20]	NA	Voltage and current measurement at PCC for input	No effect on power quality	Complex and impractical for real problem
11.	Random Forest classifier (RF)	[31]	Single, multi-inverter≤ 0.037,0.115 sec	Voltage & current measurement, f_s=1KHz	Work with multi-inverter	NDZ≠0

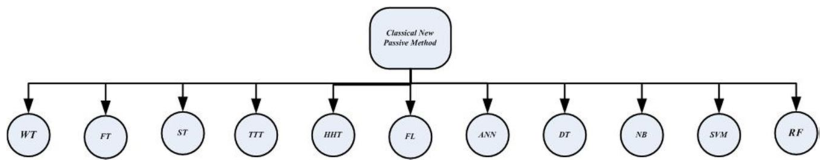

Figure 4: Classical New Passive Methods

Active Methods

On the basis of system reactions via the locally recorded signal, active islanding techniques introduce disturbances into the supply system to detect islanding scenario. They have been utilised in literature for inverter-based (single and multi) distributed generation systems [16]. An appropriate islanding detection time and a modest or even nil NDZ. Despite their benefits, they degrade the quality of the power. The best techniques are displayed in Fig. 5 and Table IV.

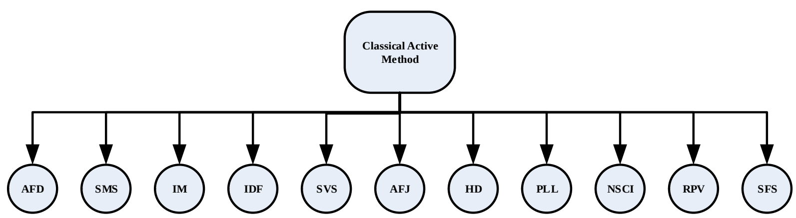

Figure 5: Classical Active Method

TABLE IV: IDMS OF CLASSICAL ACTIVE TECHNIQUES

S. No.	IDMs Name	Reference	Detection Time	Vivid	Advantage	Disadvantage
1.	Active Frequency Drift (AFD)	[26],[20]	≤ 2 sec	Voltage changes when the inverter's current is perturbed. crossing zero	Simple, powerful, and uses several inverters	NDZ≠0, bad performance for high Qf
2.	Slip Mode Frequency shift (SMFS)	[13],[27]	0.2 sec	Control of current and voltage at PCC in relation to frequency	Simple, powerful, and uses several inverters	NDZ≠0, bad performance for high Qf
3.	Impedance Measurement (IM)	[26],[27]	≤ 12 cycles	Measurement of local system impedance	Negligible NDZ, affordable	Bad outcomes when using several inverters
4.	Impedance Detection at specific Frequency (IDF)	[20],[26]	0.04-0.06 sec	Current harmonic injection at a particular frequency into PCC	Ability to detect islands under various circumstances	Multi-inverter nuisance trip and NDZ≠0

5.	Sandia Voltage Shift (SVS)	[13],[27]	≤ 2 sec	Positive feedback to the amplitude of the voltage	Negligible NDZ, easy, and cheap	Slight degradation of power quality
6.	Active Frequency Jump (AFJ)	[20],[26]	≤ 4.5 cycles	Variant of AFD that resembles impedance measuring	Using a quick detection, the grid is injected with less electricity.	Poor results with multiple inverters
7.	Harmonic-Distortion based (HD)	[1],[20]	0.016-0.24 sec	Three indices (THD), (DF), and Harmonic measure voltage variations on an island. Factor Amplifying (HAF)	Low price and quick detection	NDZ≠0 and more analysis are required with higher Qf
8.	Phase Locked Loop (PLL)	[13],[20]	0.103-0.104 sec	The Goertzel algorithm for second harmonic measurement	No impact on the grid's stability, comparable results with all loads, and quick detection	It may influence on the PLL.
9.	Negative Sequence Current Injection (NSCI)	[13],[20]	≤ 0.036 sec	Using the VSC to inject a negative sequence current	Quick detection, unaffected by load variations	At PCC, it can lead to an unbalanced voltage.
10.	Reactive Power Variation (RPV)	[27],[28]	≤ 0.17 sec	Considering the connection between frequency and reactive power. (Control for Q-f droop)	Quick detection, easy, and efficient multi-inverter	Ineffective performance for the higher Qf
11.	Sandia Frequency Shift (SFS)	[1],[9],[27]	≤ 2 sec	AFD expansion that increases the frequency of positive feedback	Negligible NDZ, inexpensive	NDZ≠0, bad performance for high Qf

B. Remote Methods

The grid and any type of system, including inverter-based (single & multi), AC and DC microgrids, must communicate in order for the remote techniques to work [17]. The zero NDZ and DG-type independence of the remote approach, which allows it to be used with all four major categories, are its main benefits. Since it is anticipated that as the smart grid matures, the power system's communication layers will rise, the new islanding detection systems with a communications-based approach and smart grid devices are becoming more and more intriguing [18]. However, communication-based solutions call for utility company participation in the installation of islanding detection schemes is the main challenge. The primary categories of remote approaches are depicted in Fig. 6 and Table V.

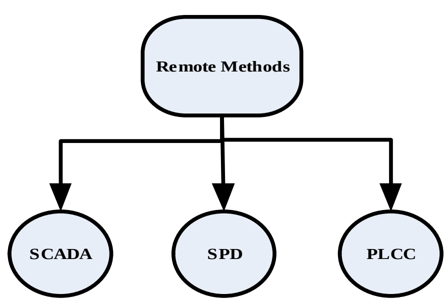

Figure 6: Classification of Remote Methods

TABLE V: IDMs OF REMOTE METHODS

S. No.	IDMs Name	Reference	Detection Time	Vivid	Advantage	Disadvantage
1.	Power Line Carrier Communication (PLCC)	[1],[20]	< 2 sec	For each DG, the system has a signal generator and a signal detector.	NDZ=0, independent of the DG type	Expensive, interference with other signals
2.	Signal Produced by Disconnect (SPD)	[13],[26]	< 2 sec	SPD communicates over a telephone line, microwave link, or some other method.	NDZ=0, independent of the DG type	expensive and intricate in its functioning and construction
3.	Supervisory Control And Data Acquisition (SCADA)	[9],[20],[28]	may take longer than two seconds	Based on keeping an eye on the condition of every circuit breaker that might island a DG	NDZ=0, regardless of the DG type	In terms of installations and operations, expensive and complicated

V. IDMS COMPARISON OF AC MICROGRIDS VS. INVERTER-BASED (SINGLE AND MULTI) MICROGRIDS

Only a few of the local IDMs described above have been put to the test by the researchers in order to assess how well they operate in AC microgrids. It has been established that the traditional passive methods UOV, UOF, PJD, and Voltage Harmonic, as well as the active methods SVS, SFS, SMS, and AFD, do not perform well in ac microgrids.

Even more complex systems, such as those in Table IV, have a better ability to operate on a multi-inverter basis, but they have not been researched in AC microgrid. Furthermore, because the RoCoF measurement is so sensitive to minute changes, it has been demonstrated that it significantly harms small-scale island microgrids [19]. Therefore, even a minor disruption in an island microgrid could result in frequency instability or a whole system failure. The active technique's injected harmonic – Harmonic Distortion was also demonstrated to have a detrimental effect on the quality of power for AC MGs operating in island mode [20]. The aforementioned debate supports the idea that for AC microgrids, the IDM's options are more constrained. It is necessary to conduct additional modelling, research, and lab experiments on the IDMs in order to enhance AC microgrid performance.

VI. IDMS FOR DC MICROGRIDS

These techniques essentially depend on constantly checking the measured system characteristics, like voltage and current. When islanding happens, the protective devices will detect it and send out a control command if these parameters meet an islanding detection threshold such as over/under voltage. (For instance, disconnect or enter islanding mode) [21]. When there is conflict, passive approaches can be quite powerful a large imbalance in power supply and demand before an islanding event However, these approaches perform worse if there are no or almost no incompatibilities since a significant amount of NDZ is inherited. Under/over voltage and the autocorrelation function of the model current envelope are two other passive approaches for DC microgrids [22]. Due to its many advantages over AC microgrids which includes small power losses, increased comprehensibility and enhanced power quality network operators and suppliers are switching towards DC microgrids. For DC microgrids, very little or no IDMs have been proposed and they are still in their existence. The following are some of the suggested passive IDMs for DC microgrids:

- Rate of change of current (ROCOC)
- At PCC, frequency and voltage deviation
- Rate of change of voltage (ROCOV)

ROCOV and ROCOC can be calculated from the below equation stated as follows:

$$RoCoV = \{V_n - V_{(n-\Delta n)}\}/\Delta n \quad (5)$$

$$RoCoC = \{I_n - I_{(n-\Delta n)}\}/\Delta n \quad (6)$$

In the above equation (5 & 6), 'n' is the number of algorithm steps, Δn is the step size, V_n & I_n are the magnitudes of voltage, current at the n^{th} sample respectively. Real power imbalance forces a variation in voltage and current during islanding. Therefore, a value will be assigned to ROCOV and ROCOC magnitude for islanding detection. The results show that there is no differentiation between islanding and other non-islanding situations that can be met by the aforementioned solutions [23]. Frequency and voltage deviation at PCC is another passive method for DC microgrids that depends on the DC voltage from the microgrid reacting to the frequency and voltage fluctuations of the AC grid side. For an actual setup, this technique requires a communication link [24]. There needs to be more research done on active ID techniques for DC microgrids, “of course”.

VII. CONCLUSIONS

Most IDMs have undergone review. And the taxonomy of IDMs has undergone revision. It includes passive and active techniques for microgrids with Single-Multi, AC & DC Inverters. Numerous Active and Passive methods have been analysed and contrasted. The findings demonstrate that passive approaches have a large NDZ, a quick detection time, and an easy implementation. Even if active techniques have a small NDZ, power quality gradually deteriorates with time, especially as the number of DGs rises. Although remote islanding detection techniques can be used with all structure types, incorporating inverter-based (Single & Multi), AC & DC microgrids with zero NDZ, doing so requires communication lines which adds to the cost of the system. They also work with utility companies to deploy the islanding detection technique, which is not the best option. Also, only a few of the available islanding detection techniques in the market have been studied for AC microgrids which indicates that many more studies are still needed for the proper and smooth functioning of the system. DC microgrids have fewer possibilities for islanding identification because they are still in their infancy.

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