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State of the art on Islanding Detection Methods in a microgrid

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ABSTRACT

The islanding phenomena is one of the crucial requirement in developing a concept of microgrid and need to be detected reliably and accurately. This will improve safety concerns and power system parameters violations, such as voltage collapse and frequency variations. This article presents the basics and need of islanding in the microgrid, with state of the art on islanding detection. This also includes the classification of various islanding detection techniques with their respective tools considered for the detection. The conventional 'local' techniques such as passive, active and hybrid methods along with the 'remote' Techniques based on communication, are analysed and discussed in detail along with the merits and the shortcomings of each approach. This paper also discusses artificial intelligence as an improvised tool for islanding detection, and several intelligent techniques are presented in the paper for comparison and analysis..

Keywords: *Distributed Generation, Microgrid, Islanding, Islanding Detection, Signal Processing, Artificial Intelligence*

1. INTRODUCTION

The idea of a microgrid is an evolutionary concept that dates back to a very earlier time where the idea of power distribution was in its initial phase and started locally. It was later that the power system was made interconnected and thus forming interlinks to form grids. So, today's microgrid is the older pick from our conventional idea behind ancient power systems. The reason today it has gained popularity is due to the high penetration of Distributed Energy Resources and a significant dependency on electricity due to the growing demand of energy. The other possible merits that a microgrid can provide are that; it's eco-friendly, easy to design, control, manage, and can be utilized with renewable sources very efficiently.

The microgrid can be defined as [1]: "Microgrids comprise LV distribution systems with distributed energy resources (DER) (microturbines, Fuel cells, PV, etc.) together with storage devices (flywheels, energy capacitors, and batteries) and flexible loads. Such systems can be operated in a non-autonomous way, if interconnected to the grid, or in an autonomous way, if disconnected from the main grid. The operation of micro sources in the network provides distinct benefits to the overall system performance if managed and coordinated efficiently."

The essential components of microgrid include Distributed Energy Resources (DER), loads, master controller, smart switch, protective device, communication system, control system and automation system. DER's are introduced with the energy storage devices so that the reliability of sources during its off time is maintained.

Beyond clean energy generation for more sustainable societies, the integration of massive Distributed Power Generation Sources (DPGS) poses many challenging issues to the distribution power grid and to the utility [2]. The energy from renewable sources is always time-varying and fluctuating, that may affect the system parameters and stability if there is a high degree of penetration of such energy resources. Moreover, the resilience in case of abnormal climatic conditions must be addressed. Another issue related to DER's is protection, because the conventional power systems are radial network and power flow is always unidirectional from source to load, while, with integrated DER's the structure of a system is active and no longer radial, so, there exits various problems. These problems include a decrease in fault current detection capability, a decrease in reach of the impedance relay, and the in-effective auto-closure operation of circuit breakers due to Distributed Generation (DG) connected in parallel with the network. DG are (is) usually aided with power electronics technology for their proper linkage with the system. The inclusion of a large number of power electronic converters increases the amount of non-linearity, which will be reflected as the distortion of current and voltage waveform at the output side and results in harmonic pollution of the power grid [3].

The microgrid consists of all DER's synchronized with the existing frequency of the conventional grid and it can serve two purposes. Firstly, during grid-connected mode, a microgrid can operate in parallel with the main grid and satisfying the energy demand of local loads. Secondly, during faults or outages in the grid, it can perform the role of an autonomous entity in the form of islanding. Even during the partial or complete blackout of the main grid, the islanded grid can energize some or entire portion of loads connected to it. However, the islanding phenomena have adverse effects on the power system stability and power system protection utilities. Moreover, the PV inverter during islanding mode is having an adverse impact on the utility feeder connected near it. For instance, temporary fault on a feeder should be cleared by operation of fast operating recloser & fuse should blow out only in case of a permanent fault. With the involvement of DGs in the system, the level of fault current as seen by both fuse & recloser will be different. Due to the

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integration of PV in an unbalanced type feeder, the harmonics in three-phase currents and voltages and may get maximized. Total Harmonic Distortion (THD) of instantaneous grid-side current can severely damage the equipment.

This article focuses on the study of the islanding condition and analyzing various techniques for its detection. Section Ⅱ of the article discusses the necessity of islanding detection. Section Ⅲ describes various methods of islanding detection and their relative merits and drawbacks. Section Ⅳ presents the techniques of artificial intelligence used for islanding detection. Section Ⅴ of the article presents the comparative analysis of all islanding detection techniques discussed.

2. THE NEED OF ISLANDING DETECTION

During the condition of the islanding in a micro-grid, following problems may arise:

(1) In the case of higher DG capacity that is more than the load limit, thermal constraints may be observed on load side utilities.
(2) With the event of islanding, reversed power flow can be observed from lines, as power flow may be changed from unidirectional to bidirectional.
(3)Voltage collapse issues with downstream loads.
(4)Protection challenges like false tripping of feeders, blinding of protection and unsynchronised reclosing, etc.
(5) Safety concerns for line workers in the event of maintenance. This may be compromised as the grid can carry power from DG sources even though it is disconnected from the main grid.

The successful islanding phenomena occur when load demands will be met successfully by the DG connected in the microgrid and the voltage and frequency are maintained in respective limits. As the DG output is not constant and depends on the accessibility and availability of renewable sources, the balance between generation and load is difficult to achieve [4]. The islanding needs to be detected for the appropriate management of energy in the microgrid. Moreover, the control and protection strategy with DG connection mode also largely depends on microgrid's connection to the main grid. The probability of islanding based on penetration of DGs, protection settings and load characteristics is discussed in [5]. The load to generation ratio is dependent on various factors like the maximum power level of DG and/or seasonal variation in load and generation profile. Figure 1 shows the typical PV based system connected in parallel to the main grid to supply the load.

The performance index of islanding detection techniques includes reliability, selectivity and minimum perturbation [6]. The islanding detection technique should be able to detect the islanding in any system condition or low/high level of penetration of DG, etc.), which is termed as reliability. The technique must be able to distinguish between system fault condition and islanding condition. The fault condition is basically a non-islanding condition. This property is known as the selectivity of the islanding technique. However, the islanding detection method must not interfere with the power system and should not degrade the power quality level of the power grid beyond the specified limits, which is called the minimum perturbation. The islanding detection is to be carried out within the norms and standard of IEEE[7], and the detection must be successfully completed within 2 seconds after the event of islanding (has occurred).

The islanding techniques are broadly classified as 'local techniques' and 'remote techniques'. The local technique includes passive, active and hybrid methods for islanding detection. In passive methods, the islanding detection is carried out by identifying a violation of the limits in power system parameters measured at the point of common coupling. In the active method, an injection of any disturbance signal is made in the system to force the parameter to be made measurable for islanding detection. The combination of both active and passive methods forms hybrid methods for detection. The remote techniques deal with the detection of islanding only by communication methods without involving any power system parameters.

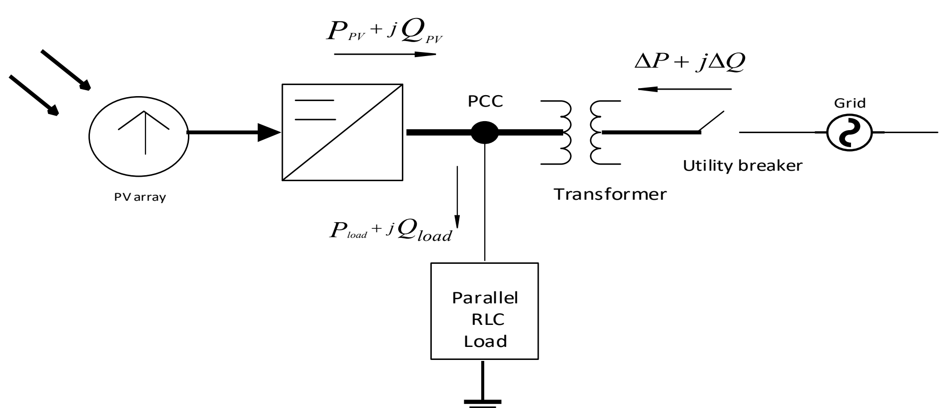

Fig.1 Simplified Model of DG system

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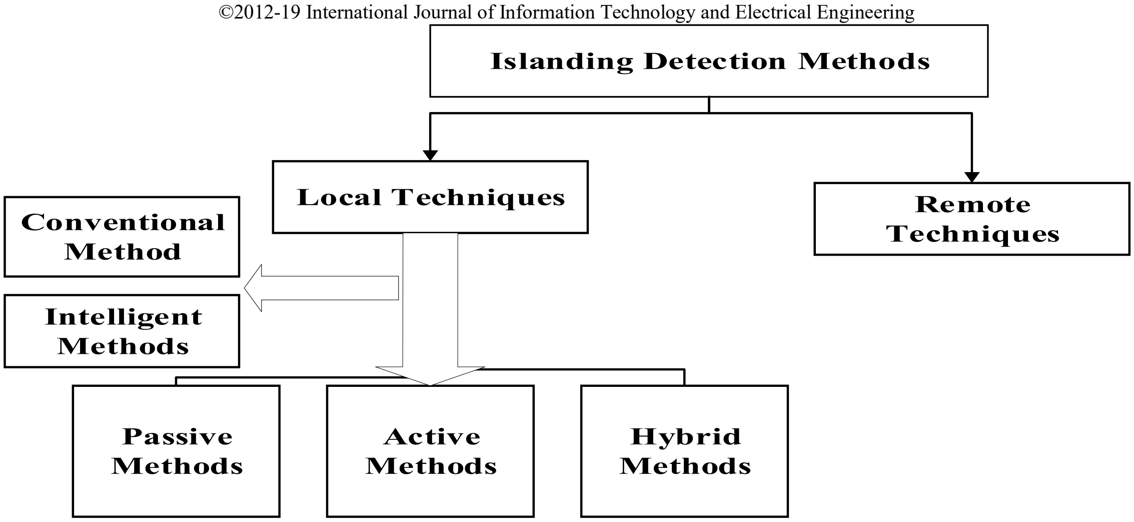

Fig.2 Classification of islanding detection techniques

(A) Passive Methods

(1) OUV/OUF Detection

Over/under voltage (OUV) and over/under frequency (OUF) method monitors the system's voltage and the frequency at the point of common coupling (PCC) to decide whether the islanding has occurred or not [8, 9]. The OUV/OUF relay can sense the violations limits which are typically defined as +10/-15 % for voltage and +1/-1% for frequency (may vary for some countries)[6]. If ΔP and ΔQ are the real and reactive power output of grid, P_{DG} and Q_{DG} are real and reactive output power of the grid, then considering P_{load} and Q_{load} as the real and reactive output power of load, the energy balance equation becomes

$$P_{load} = P_{DG} + \Delta P \quad (1)$$

$$Q_{load} = Q_{DG} + \Delta Q \quad (2)$$

After disconnection of the grid, in an islanded mode, the real power output from the grid is zero and so real power output of DG is forced to match with the real power output of load. As there is a direct relation between active power and voltage, the voltage at the grid are forced to adjust in proportion with active power unbalance. The same is applicable to a change in reactive power and frequency. The undesirable case of this method exists when in pre-islanding conditions, the DG generation is sufficient to cater to the available load in the system. In this condition, pre-islanding real and reactive power supplied by grid is zero. In this case, there will not be any change in the voltage amplitude and frequency at the event of islanding. Hence it is not possible for OUV/OUF method to detect the case of islanding. This region bounded by OUV/OUF is called Non Detection Zone (NDZ).

(2) Harmonic Detection (HD) Method

The DG available in the system with converter usually produces harmonics depends on switching and other properties of semiconductor devices. Due to half-wave symmetry of power electronics inverters, the even harmonics are nullified and only odd harmonics like3^{rd}, 5th, 7th and higher order are present. According to IEEE 1574 standard, THD in the system must be less than 5% to comply with the standard of power quality. The level of grid impedance affects the amount of voltage harmonics generated. During normal grid-connected mode, the value of system source impedance measured is low due to the paralleling of DG sources with the grid. However, during islanding mode the value of source impedance may be higher. This change may be at least an order of impedance magnitude for a low voltage DG [6]. This will cause a high level of harmonics and it can be used as an aspect for islanding detection. The islanding detection requires only 3rd, 5th, and 7th harmonics to be detected. The PLL scheme for harmonic synchronization monitoring of 3rd, 5th, and 7th harmonics is discussed in reference [10], where qd transformation followed by 3rd order Butterworth filter is implemented to extract each individual harmonic.

The above method has an advantage of lower NDZ but suffers from some shortcomings, like the switching on/off of non-linear load in the system may change the level of harmonics and it may be wrongly detected as an islanding. Another problem lies with DG Inverters & their counteraction to increase the distortion of voltage to inject clean current can affect the detection adversely. The property of selectivity remains a significant challenge for this method as it is very hard to distinguish among the sources of harmonics entering the system and may result in false tripping. To overcome these difficulties, the strategy based on the estimation of energy based on an error between measured and estimated values of higher-order harmonics using kalmann’s filter [11] is implemented. This method greatly improves the selectivity to detect the selected harmonics for detection.

The non-ideal characteristics of grid-connected inverter produce multiple fundamental frequencies in output voltage due to dead time. These harmonics voltage can be used as a signature for islanding detection[12]. The dead time is introduced intentionally to avoid short circuit conditions in same leg of three-phase voltage source inverter. Due to current and voltage harmonics resulting from non-linearity of an

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inverter, high-frequency impedance is obtained, which is a tool for islanding detection.

(3) Rate of change of frequency (ROCOF) method

At the time of islanding, due to active power mismatch, a transient situation occurs with narrow frequency variations but with a higher rate of change. This frequency variation with higher rate of change is normally available in the system for a few cycles (usually 2 to 50). This rate of change of frequency can be a tool for islanding detection. The ROCOF relay is used to monitor the voltage waveforms and can shut down DG inverter if the rate of change of frequency exceeds the pre-set value. In reference [13], the ROCOF relay is designed and tested for various performance like external faults, non-linear loads and mismatch in active power balance. ROCOF relays may fail to operate when active power mismatch is very large enough that it cannot sense the slow rate of change of frequency. The paper [14] presents a combined technique of islanding detection in which the rate of change of voltage unbalance (ROCOVU), rate of change of frequency (ROCOF) and rate of change of reactive power (ROCOQ) are used to improve the selectivity. Two ways implement the method, either by calculating the product of ROCOVU and ROCOF or by calculating the product of ROCOVU, ROCOF and ROCOQ. If they exceed their threshold limits the islanding detection is detected.

(4) Phase Jump Detection method (PJD)/Impedance Difference Method

In the event of islanding, there may be the possibility of reactive power mismatch. Due to which a phase difference created between the inverter output voltage and output current. This change can be used for a tool for islanding situation detection. The phase shift is detected by utilizing zero crossing of voltage with reference to current phase at some instants. The Phase Lock Loop (PLL) in DG inverter for synchronization is implemented in reference [15]. Where rising or falling edge is used for zero-crossing detection. During islanding, the change in voltage level is abrupt but inverter output current remains constant due to mapping with PLL loop, so in the next cycle of zero-crossing the phase error exists between PCC voltage and output current. The amount of phase error acts as a tool for islanding detection.

A novel technique is presented in the article[16]. The proposed algorithm in this article uses extracted positive sequence PCC voltage and its image. The image has the same amplitude and frequency as that of original voltage so its waveform is superimposed on the original waveform during normal operation or sudden load variation. In this article, phase shift between PCC voltage and its created image is detected. Both waveforms will not match during occurrence of phase mismatch. This condition occurs during islanding conditions only and hence can be able to detect islanding. A similar methodology using impedance difference as a tool for islanding detection is proposed in paper [17]. The reference impedance is tracked at a specific band of frequency from PCC voltage and current. The magnitude of both reference impedance and calculated impedance is compared for the detection of islanding.

The algorithm focuses on the natural occurrence of harmonics and Fast Fourier Transform (FFT) analysis of PCC voltage and current is proposed in paper[18]. For each harmonic present, corresponding frequency-dependent impedance is calculated. The algorithm then selects a harmonic and find a derivative of line that passes through the harmonic and its previous harmonic and logically decides islanding from the direction of the rate of change of the above derivative.

(5) Voltage Unbalance (VU) Method

In this method, the component of positive sequence voltage and negative sequence voltage are utilized. The VU is defined as a ratio of negative sequence voltage to the positive sequence voltage of the unbalanced three-phase output voltage of DG during islanding event. The paper[19] proposes the logic-based algorithm for islanding detection using average voltage unbalance over a cycle, voltage unbalance variation and Total Harmonic Distortion (THD) of current. The paper calculates the change in voltage THD from various different harmonics. The change in voltage unbalance and/or change in negative sequence voltage is proposed in a multi-criteria based detection scheme.

The comparison table for various passive methods is as shown in Table 1.

TABLE-1

	Method	NDZ	Advantages	Difficulties
1.	OUV/OUF	Large	Easy to implement Low cost	Unpredictable response in some system conditions
2.	HD	Larger for Large Q	multi-inverter operation	Less selectivity, Threshold selection
3.	ROCOF	Small	easy implementation	Threshold selection, Less reliable in classification
4.	PJD	Medium	Work with Multi-inverter operation, Can accommodate site specific method No impact on system	Threshold selection
5.	VU	Medium	Higher selectivity	Not applicable to single-phase system

(B) Active Methods

(1) Frequency drift methods

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The frequency drift method is implemented by adding an intentional disturbance in system frequency by means of some appropriate feedback. This intentional up or down drifting of frequency is possible only after islanding occurs due to the presence of disturbance. In Active Frequency Drift (AFD) method, during islanding the output current of PV inverter is a sinusoid having the frequency slightly more than utility voltage (up drift)[6]. The dead time is introduced during the occurrence of zero-crossing of inverter output current before it starts its next half cycle. Similarly, the dead time is introduced at the other half cycle during zero crossing of inverter current. If this distorted current waveform is applied to resistive load in an islanded mode, voltage response follows the trajectories of distorted current and reaches its zero crossing in a shorter range of time than it would have achieved in case of a purely sinusoid case. This introduces the phase error between the voltage at the node of inverter and output inverter current due to which the PV inverter starts increasing frequency of the current to reduce the phase error. This process continues till frequency is drifted out to be able to detect by OUF zone. This method depends on the quality factor of load under consideration and may have larger NDZ.

The ratio of dead time to utility voltage considered for one-half cycle of utility voltage is called as chopping fraction (CF). To increase the effectiveness of AFD scheme, paper [20] proposes the AFD along with a positive feedback loop scheme (AFDPF) in which '*cf*' is increased though positive feedback according to increase in deviation of frequency from the normal value. The mapping function is used for mapping the error in sampled frequency with real numbers. The advantage of this scheme is it offers lower NDZ and in a practical case, when frequency error is negative due to any other circumstances during islanding, '*cf*' becomes negative due to positive feedback, which results in reinforcing drifting down the operation of the frequency instead of counteracting on it.

In another method of frequency drift, called Slip Mode Frequency (SMS) shift, uses positive feedback to phase of PCC voltage to shift the phase. PV inverters operate at unity power factor (UPF) while in SMS method current-voltage phase angle of the inverter is non zero and is a function of the frequency of PCC voltage. "The phase response curve of an inverter is designed such that the phase of inverter increases faster than phase of RLC load [21] with unity power factor in a region near utility frequency." After an island is formed, the phase frequency operating point of load and PV inverter must be an intersection of load line and inverter phase curve response. With positive feedback due to any disturbance away from set frequency, the phase error increases due to instability and thus system is driven to a new set point till the frequency is driven out of OUF protection window. The problems with this method arise if some loads have faster phase response characteristics than the PV inverter and phase error due to transient time may be large.

A new scheme by combining both AFD and SMS schemes is obtained by injecting both frequency and phase signals using a digital PLL loop[22]. After islanding, voltage waveform follows distorted current waveform in case of the AFD method (for pure resistive load) while the starting phase of voltage and current is controlled by the function of the frequency of output voltage in case of SMS method. So, resulting operating point is decided by governing equations of both the schemes [22] and the advantage of this method is fast detection time and smaller NDZ. The article[23] demonstrates the effect of load parameters like quality factor and resonance frequency of RLC load and its impact on NDZ of active frequency drift methods.

(2) Impedance Measurement

During the instant of islanding, the inverter output voltage changes due to real power mismatch where the load power requirement is forced to match with DG's power generation. However, the current from grid-tie inverter is a function of load impedance. The impedance as measured from an inverter, can be calculated as the ratio of change in voltage to the change in current, during islanding. The estimation of impedance is a tool for islanding detection, which is carried out by two methods-harmonic injection (HI) method and PQ variation method. The HI method works on the principle of injecting harmonic current into the inverter to extract the corresponding voltage harmonic at some specific frequency. The choice of harmonic frequency is such that it does not coincide either with the resonance of current controller frequency or grid resonance frequency. The injection of two different harmonic frequency components, followed by calculating grid impedance at two different points is carried out in [24] using statistics technique.

The other method which uses only one specific frequency is described in [25]. In this method, the inverter injects inter-harmonic in the grid to measure its response and to translate measured impedance value from a particular frequency into the fundamental frequency. HI method may fail in terms of accuracy when there are multiple inverter units running in parallel. A strategy is needed to prevent interference of more than one inverter injecting the high-frequency signal. The study in [26] proposes the solution to this problem, in which a master inverter detects islanding, it injects secondary high-frequency signal which is detected by other slave inverters that need to adapt to new conditions of working mode.

PQ variation method is used only if the strategy of control used for an inverter is 'PQ control strategy'. The grid impedance is calculated based on two stationary working points and the unknown being the grid impedance and voltage at supply terminals. It is followed by solving two stationary point equations. The principle of the method is to produce a small disturbance in the output of inverter in case of periodic real and reactive power. The orthogonal system generation block is required to implement PQ control in a single-phase system and Clarke transformation block in case of a three-phase system [27]. The grid impedance is assumed to be linear in the case of two working points of an inverter.

(3) Phase-Locked Loops (PLL) Techniques

The principle of PLL is to synchronize the control system with the grid voltage. It takes input as voltage measurements from the output of voltage source converters and generates an estimation on system frequency and phase angle. The paper [28] presents a PLL technique by modifying each output cycle of inverter current reference to affect the generated current to a smaller extent. It aims to synchronize inverter output current with grid voltage in order to extract ideal sinusoidal current reference and maintaining the unity power factor. This sinusoidal current signal synchronized with cycle is later injected to alter inverter current angle and this feedback signal is extracted at PCC. The advantage of the method is that the extracted feedback signal gives information about grid impedance change and can effectively detect islanding and it does not affect zero crossing of the current signal.

The paper [29] proposes the advanced PLL technique by adding another closed loop termed as frequency locked loop (FLL) which utilizes positive frequency feedback by comparing the instantaneous frequency with nominal line frequency. The grid frequency is time-variant during islanding detection process and it depends on the resonance frequency of load, and if both frequencies are not matched, it can lead to phase error. The FLL loop is used to modify constant resonance frequency and to make phase error nearly diminished to zero. The advantage of adding FLL is accuracy and robust operation of the detection process.

(4) *Voltage Drift (VD) methods*

During the normal grid-connected mode, there is no drifting associated with voltage. However, during the instant of islanding, the grid voltage is made to be drifted out either by the positive feedback of current or by altering the reactive power. The Sandia Voltage drift (SVD) method [21] uses positive feedback to the amplitude of the root mean square (rms) value of voltage. After grid disconnection, voltage level will decrease considerably and it will reduce even more due to the action of Ohm's law response of RLC load impedance to the reduced current. This in turn reduces PV inverter output current that leads to downfall in voltage which can be detected by OUV protection window. The main drawback of this method is decrease in the operating efficiency of PV inverters due to various maximum power control points.

The active methods are analyzed and comparison is shown in Table-2.

TABLE-2

	Method	NDZ	Maintenance	Advantages	Difficulties
1.	AFD	Large for high Q-load	Low	Easy to implement	Cannot handle concurrent in micro-controllers
2.	AFDPF	Large for high Q-load but less compare to other methods	Medium	Highly effective and selective	Instability issues
3.	SMS	Large for high Q-load	Medium	Highly effective	Instability problem with higher penetration of PV
4.	Impedance Measurement	Large for high Q-load	Medium	Easy implementation high speed of operation	Effectiveness decrease with increase of inverter
5.	VD	Medium	Medium	Easy implementation	Instability problem higher penetration of PV

(C) Communication Methods

(1) Power Line Carrier Communication (PLCC*)*

This method relies on the communication between PV inverters and grid. A transmitter (T) is placed near the line protection switch of the grid and a receiver (R) is positioned somewhere in the proximity of inverter near the PCC. The transmitter sends the signal to the network and the receiver installed at every DER's will receive the signal. This works continuously in time. The receipt of the signal is continuous during grid-connected mode and whenever receiver fails to listen the signal the islanding is said to be detected. The characteristics of the PLCC signal required for transmission is discussed in [30] and receiver design is also implemented based on Digital Signal Processing (DSP). The proposed method does not interfere with power system parameters and power quality during islanding and is highly reliable. The only disadvantage is its high cost of a transmitter for high voltage level and standardization of signals used for communication purpose. Moreover, all related protocols for signal transmission needs to be addressed. Another communication-based technique by injecting subharmonic voltage through the series injection transformer is reported in [31]. A subharmonic signal poses advantage of passing through power transformers without the need of a coupling capacitor and it also propagates through longer distance with a very little attenuation.

(2) Impedance Insertion method

This method inserts either a reactor or a capacitor during the islanding instance. When the reactor is inserted during islanding, the voltage drops and frequency rises. In the case of a capacitor, the voltage increases and frequency drops [32].Due to insertion of energy storage elements, the mismatch occurs between reactive power generation and load and so voltage and frequency are varied at the distribution side. The frequency deviation is detected then near distribution side. The insertion of a capacitor is generally preferred more as compared to reactors, but the problem is increased cost of capacitor banks and low response time due to switching of capacitors, along with some intentional delay associated with switching of capacitors to allow the detection of frequency variation.

(3) Transfer trip scheme

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This method includes all the Circuit Breaker (CB) which are part of islanding to be monitored and linked to a central control unit. If the islanding is detected, the central algorithm detects the islanded area and signal is sent to all generators either to remain operational or to shut down. The mode of operation is presented in paper [33] and communication media like SCADA, satellite communication, optic fiber Ethernet and leased telephone lines are discussed. The cost of the system and design compilation are the challenging issues for this scheme.

(D) Hybrid Techniques

Hybrid methods are generally the trade-off between the occurrence of large NDZ in case of passive methods and power quality issues in case of active methods. In hybrid methodology, active injection of a signal is applied only if the passive method suspects the islanding condition.

The problem with VU method was the selectivity between islanding condition and load switching and that of HF signal injection method was that it could detect islanding only at zero crossing of grid voltage. The hybrid method gains advantage of both of these and eliminates their respective disadvantages. The papers [34, 35] proposes the hybrid technique based on voltage unbalance (VU) method and high frequency (HF) impedance method. Firstly the deviation of voltage at PCC is measured passively and if it is outside the limits, HF voltage is injected into the system which detects the impedance at a specific frequency. The impedance of three phases of a system is calculated at PCC and if the estimated impedance is outside its permissible limit, the islanding detection is confirmed.

The islanding detection is carried out in limited definite voltage cycles as proposed in paper [36]. Itutilizes the rate of voltage change for the first five periods of voltage cycle and check its magnitude with corresponding set limits. If the magnitude of rate of voltage change is between the lower and higher set points, islanded is only suspected and active method in form of real power shift (RPS) is introduced and then the rate of change of voltage for 20 cycles is calculated again and if it exceeds the set limit, the islanded is detected and correspond to it, the real power output of DGs are made to adjust again. This method improves the property of the selectivity of a system.

The combination of Voltage Unbalance (VU) and frequency setpoint techniques is presented in paper [37], which varies the frequency based on the amount of voltage unbalance present in DG. If the frequency drop remains persistent and goes below a certain standard, it means that the utility grid to which DG is connected is not energized and thus islanding has occurred. If after lowering the frequency set point, the frequency remains close to the grid frequency, utility grid is still connected and so no islanding has occurred.

A novel and robust hybrid islanding detection technique by combining ROCOF relay for measuring the rate of change of frequency and active SMS method is presented in paper [38]. The ROCOF relay is activated only if both 'rate of change of frequency change' and 'voltage phasor at PCC'are deviated from threshold values. The islanding condition is only suspected and followed by initiating the positive feedback SMS method to cause the phase shift in the system and to detect islanding condition.

The hybrid islanding detection using the measurements of various electrical quantities exceeding its limits during islanding and the communication method with the grid via power line communication medium is proposed in paper [39]. The passive methods monitor and provides the values of voltage harmonics and THD of voltage waveform at PCC to the communication channel via an interface device. The islanding is detected if PLC signal communication is absent on the receiver in conjunction with an increase in the THD measurement of voltage at PCC.

(E) Intelligent Techniques

Intelligent techniques have grown attention to various researches for islanding detection operation due to its robustness and superiority as compared to conventional techniques. The extraction of hidden features of the measured signal from the signal processing (SP) techniques serves as an input to artificial intelligence (AI) classifiers to discriminate between islanding and non-islanding conditions. The signal processing techniques provide with features like time-frequency distribution (TFD) of a time series which can simplify the analysis of signals [40]. Several AI techniques that are used for islanding detection are Fuzzy Logic (FL), Artificial Neural Network (ANN), Probabilistic Neural Network (PNN), Decision Trees (DT) and Support Vector Machines (SVM). First, the SP using Wavelet transform (WT) is discussed and then intelligent techniques are reviewed in brief.

(1) . *Wavelet Transform (WT)*

Wavelet is defined as a set of components in the form of small waves localized in definite space when mathematically modeled are used to represent the data or function. The localization feature of wavelets and frequency makes the functions and operators as sparse when transformed in a wavelet domain. The primary wavelet is called as 'mother wavelet' which is extended further to permit wavelet to analyze the non-stationary signals in the frequency domain [41]. The wavelet transform is classified as continuous (CWT) or discrete (DWT). The advantage of WT is that it provides a variable window depending upon the basis functions and thus, WT is used as a tool for discontinuities and/or transients in the islanding detection.

The CWT has a major drawback of reducing the computational efficiency of various coefficients in an algorithm, so DWT is the widely preferred technique. The WT possess advantage of working in both time domain as well as the frequency domain simultaneously. The paper [42] proposes a passive method approach in which current and voltage signal data are used as an input to DWT algorithm. The Daubechies is used as mother signal and it is split into detail (D) and approximation (A) parameters for different frequency windows.

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In one of the applications of WT, the islanding detection is carried out by measuring the current signal at terminals of any distributed generator. After the islanding event, the transient component continues for a few cycles and high-frequency disturbance is observed for momentary cycles of the current waveform of distributed generators. The Haar mother wavelet along with current and third level of detail (d_3) is proposed in article [43] for islanding detection. The Haar wavelets have the least decompositions and has less detection time for detection and this technique has lower NDZ problems. The paper [44] uses wavelet multi-resolution analysis (MRA) to examine the current at PCC for islanding detection. In MRA, the input signal is sampled at the rate according to the Nyquist-Shannon sampling theorem and then signal is further processed for feature extraction. The Daubechies is used as mother wavelet and fault current of phases is passed through WT-MRA technique, and it extracts component (d_6) using Db4 as mother.

The time localization property of WT is utilized by processing negative sequence voltage and current signals received at the distributed generator to retrieve them at DG side. In paper [45], negative sequence component of current and voltage are extracted and processed using WT and further change in energy and standard deviation of detailed coefficient (D) for one cycle of current and the voltage signal is used to discriminate between islanding and non-islanding conditions. This method uses Daubechies 'Db4' to reduce NDZ to zero and Db4 is preferred due to its compactness and localization property.

The transient signals of current and/or voltage waveforms during islanding provides unique signatures that are useful for detection of islanding and/or transient event. The non-stationary property of the transient based wavelet is a useful tool for islanding detection. The circuit breaker (CB) is the major protective device which breaks the circuit at PCC when any islanding event is detected based on the relay command trip. The paper [46] presents the application of the current transient signal at utility side of CB processed by WT as a tool for islanding detection. The current transient signal is measured before network CB instead at PCC and WT decomposes the signal into several signals in different frequency bands. The proposed technique eliminates the delay produced by the the relay for sending open signal orders to CB.

(2) . <u>*Fuzzy Logic (FL)*</u>

Fuzzy means a set of membership function & a decision-based approach, which is a partial truth and uncertain approach. FL is a rule based approach that is predefined by a certain set of rules and makes decisions of output parameter based on the combinations of rules. The FL approach requires less memory and can handle more uncertainties. The FL has main blocks as Fuzzification, Decision making block, fuzzy interface system (FIS) and Defuzzification. The article[47] presents the multi-criteria approach utilizing three parameters as fuzzy variables, change of voltage, rate of change of frequency (ROCOF) and rate of change of active power (ROCOP) as an input to FIS. Laying out rules based on these input parameters to decide whether an islanding is occurred or not in a system with help of defuzzification.

Another approach combining the FL with the Decision Tree (DT) is presented in paper [48] in which DT is transformed into the fuzzy rule base by developing rectangular membership function skewed at ends from the partition boundaries of DT. The voltage and current signal are retrieved at DG position, and then ROCOF, ROCOP and change in frequency are extracted and then the rule based islanding detection is carried out. The technique helps to handle the uncertainties and erroneous noise signal in the data and is superior techniques compared to other crisp classifiers.

(3) <u>*Artificial neural network (ANN)*</u>

The ANN is a mathematical model approach of a biological neuron of a human being and is inspired by the same. ANN are self-learning networks that can process any number of inputs by assigning specific weights to it and it is trained to obtain the desired output. The self-learning and self-adjusting feature to the change in inputs makes it prominent to be used as a tool for islanding detection. In [49], ANN technique is proposed for hydro-type DG with input parameters as ROCOF, rate of change of voltage, rate of change of active power and rate of change of reactive power. The output of ANN is binary logic either '1' if islanding occurs and '0' if no islanding is detected. However, with the increase in inputs to ANN, the algorithm becomes more complex and heavier. So generally, ANN in its pure form is not preferred but instead, it is combined with various other techniques to reduce the computation time and handle more uncertainties. The article [50] presents a cerebellar model articulation controller (CMAC) neural network for islanding detection to reduce training time and features detection tolerance. The input signals are voltage, frequency of voltage and phase difference between voltage and current at PCC which activates associated memory cell. The quantification, coding and combination of activated address are followed by activation of memory set from the input signal.

In[51], the ANN with WT technique has been presented to reduce the computational burden and complexity in the analysis of a three-phase signal. The three-phase current signals are combined together to form a single signal that completely represents the behavior of a system under various operating conditions. This modal signal is processed using six decomposition level DWT and using Daubechies 'Db4' signal as a mother wavelet. The input to ANN is a feature vector consisting of relative spectral energy index and is a deciding factor for islanding and it also have discrimination feature to separate out islanding and non -islanding events.

Several optimization techniques are employed with ANN to optimize the ANN parameters like learning rate (LR), momentum constant (MC) and number of neurons in a hidden layer in order to increase its effectiveness and convergence time. The paper [52] presents the particle swarm optimization (PSO) technique to optimize ANN parameters to detect islanding detection. PSO is a swarm-based intelligent approach inspired rom cial behavior of bird flocking and fish schooling.

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The absolute values of change of frequency with respect to reactive power, change in real power and change in reactive power are measured on island state. and sampling of data is done every half cycle which is fed to ANN for further processing.

The active method of islanding detection is proposed in [53], where d-axis disturbance signal injection is carried out and implements a five-layer wavelet fuzzy neural network (WFNN). During grid disconnection, d-axis signal injection in the system causes frequency deviation at terminal of parallel RLC load. The WFNN controller generates d-axis current command with the help of errors in real power and reactive power as observed during islanding. The proposed technique in this article have advantage of minimum NDZ and minimum power quality disturbance in the system. WFNN converges quickly, and network size is reduced with the advantage of handling more uncertainties.

The hybrid islanding detection based on the probability of islanding (POI) processed by DWT using an ANN is proposed in [54]. The POI is calculated at microgrid side of the interconnection using a combination of passive, active and communication methods based on utility signals measured at DG side using wavelet neural network (WNN) is performed and then POI_{ANN} is compared with its threshold limit. If POI exceeds its limits, POI_{fuzzy} is re-computed using fuzzy controller. The active method is then used once POI is conformed high using intelligent controllers, and then the measuring point of current is moved from PCC to microgrid side of utility CB. The reliability and selectivity is improved by this method and have other advantages the same as hybrid methods.

(4) *Probabilistic Neural Network*

PNN is a fundamentally developed model based on Bayesian function [55] used for pattern recognition techniques. It consists of four layers, namely input, pattern layer, summation layer and output layer. The input vector is used to define a category and network classifiers are trained using data of the known class. It develops a distribution function to evaluate the tendency of a featured vector which is contained in many categories. The paper [56] presents the phase space technique which analyze the time series in a higher-dimensional space. The features are extracted at target DG location using phase space and selects the best algorithm that extracts features of islanding detection and later classification task is performed using a PNN. It is claimed that this method gives a very high level of accuracy and is capable of discriminating between islanding and other transient conditions. Another method is proposed in [57] which integrates DWT with PNN and the classifier can filter out the different transient events on the grid accurately. The advantage being less memory space and lesser computing time as well as it reduces the quantity of extracted features of a distorted signal.

(5) *Support Vector Machine (SVM)*

SVM is a supervised learning model with associated learning algorithms that can perform the task of data classification and/or regression analysis. SVM generates a hyperplane or set of hyperplane for assigning the classification of data with well-defined boundaries. The paper [58] proposes variation in power spectral density (PSD) function of voltage and current as a tool for islanding detection using the SVM technique. The proposed method has no power quality issue on grid and is independent of power mismatch during islanding. The paper [59] implements a passive method of monitoring voltage, frequency, rotor angle, rate of change of voltage and rate of change of frequency, which are selected as the feature for SVM. The method has a higher degree of accuracy under different network contingencies and possesses minimum power imbalance level.

CONCLUSION

This article provides an extensive review of islanding detection methods available in literature for a microgrid. This state of the art review compares capabilities of all available methods with their operating principles. Moreover, their relative merits and shortcomings are also discussed. The extent of practical insights on the application & requirement of all the methods are also discussed. All methods are reviewed on the performance criteria like Non-Detection zone, power quality issues & its selectivity. The impact of artificial intelligence techniques on islanding detection in recent times is also analyzed. On the basis of this analysis, the superiority of intelligent methods over conventional methods in terms of reliability and selectivity are discussed. Furthermore, with the advent in technology, the application of the signal processing tools, followed by the artificial intelligent classifier, proved to be promising for islanding detection.

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