A Comparative Review of Islanding Detection Schemes in Distributed Generation Systems

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Received: 30.06.2015 Accepted:10.09.2015

Abstract- The main challenge in Distributed Generation (DG) Systems is that of unintentional islanding which leads to power quality issues in the utility grid. It is also considered as a major threat to personnel working in Electrical Power Systems (EPS) lines for maintenance purposes. This paper lends an overview on few detection methods which are widely recognized for industrial as well as for residential grid connected operation. Passive and Active methods which are considered to be the classical methods of detection have inherent issues such as large Non Detection Zone and poor power quality maintenance respectively. The contemporary methods such as Communication based methods and Signal processing methods which have reported small Non Detection Zone are gaining momemtum in distributed generation . Each of the islanding detection methods are evaluated based on attributes such as detection time, size of Non Detection Zone, Power Quality issues, System cost and effective with multiple DG operation.

Keywords: Islanding Detection Methods, Non Detection Zone, Distributed Generation.

1. Introduction

Renewable energy has been intensively developed in the last two decades mainly due to its practically zero emission of toxic pollutants compared to the conventional energy production such as thermal and nuclear counterparts [1,2]. The need for better power quality and reliable power supply is driving the power industry to device innovative alternate environment friendly generation techniques which balance the equilibrium between supply and demand in the power system. One such innovative technique is the Distributed Generation which is gaining primary focus in recent times. Distributed generators are those generators which are placed in the near vicinity of the load being served[3]. Distributed Generation can reduce the stress on the central power station and in the same time can work as a revenue generating unit if excess power generated is being supplied to the grid. Due to these advantages the Distributed Generation is highly preferred. Despite the number of distributed generators is in the rise phenomenally, there are numerous problems to be solved before the DG units are connected to the utility grids. The frequency and voltage deviations and the problems arising due to them can be effectively handled by installing a Automatic Load Frequency Controller (ALFC) combined with Automatic Voltage Regulator (AVR) at the DG output. The issue of islanding poses a potential threat because its severity may drive the distributed generators to malfunction or halt production. Islanding can be either intentional (preplanned) or unintentional (accidental) based on their occurrence. Unintentional islanding issues are worth focusing on since they distort the power quality of the utility grid to a large extent if found negligent [4]. An electrical island is the result of disconnection of DGs and local loads from the utility grid with the DGs still energized and remain to be operative supplying power [5]. The IEEE 1547-2003 standard specifies a maximum delay of 2 seconds for the detection of unintentional islanding and disconnection of the DG if islanded [4]. The solutions pertaining to resolve this problem is the prime focus of this paper. Reputed research laboratories are working on unintentional islanding detection since grid connected DG units are in the rise day by day. The evolution of solar photovoltaics as a distributed generation source is quite evident from recent research that its abundance of solar energy in nature compared with other renewable energy sources is immeasurable. Figure 1 shows the normal operating state of a grid connected photo-voltaic system comprising of a solar array, power conditioning unit, filtering unit, point of common coupling (PCC), local load and the utility grid. Figure 2. explains about the same system under islanded mode of operation without the installation of islanding detection schemes. It also illustrates the power irregularities faced by the local load under islanded mode of operation due to the unintentional grid shut down or failure. Prolonged operation of this condition may lead to frequency and voltage imbalance in the local load and the associated devices connected with it.

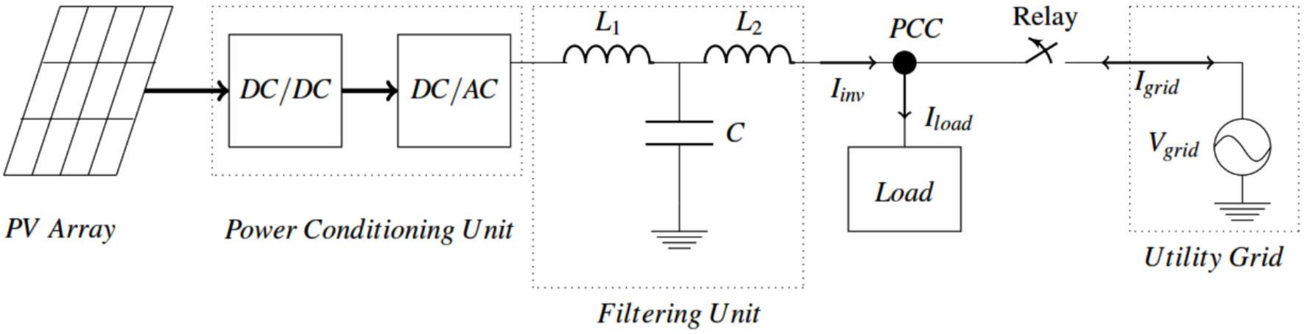

Fig. 1. Grid connected Photovoltaic System - Normal Operating Mode

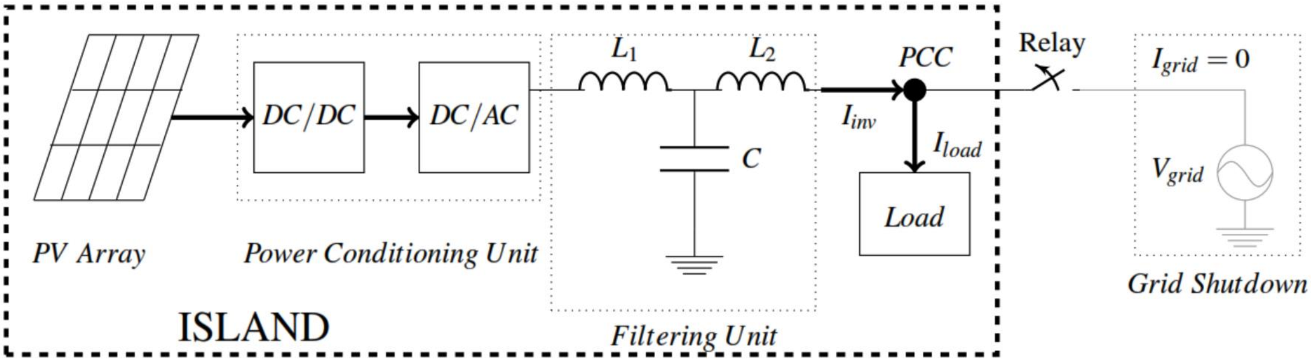

Fig. 2. Grid connected Photovoltaic System - Islanded Operating Mode

space. [6]. Variation of voltage and frequency at a point of common coupling (PCC) is related with power mismatch between DG power output and load consumption when microgrid operates in islanding condition. Especially, in the condition when DG power output and load are almost balanced, power mismatches ΔP and ΔQ are nearly equal to zero. The extent of the variation of voltage or frequency is not enough to detect islanding when the DG disconnects from grid.

2. Non Detection Zone

Islanding detection can be measured by an index called Non Detection Zone.

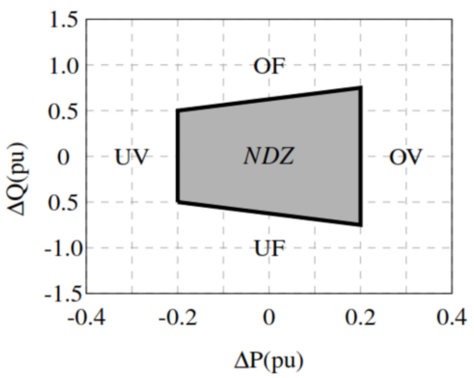

Fig. 3. Non Detection Zone (NDZ) indicating the boundaries of operation of the relays

The range of real and reactive power mismatches, which cannot cause the voltage or frequency to exceed the threshold value to detect islanding, is called Non Detection Zone (NDZ). The measurement of NDZ based on monitoring voltage, frequency or phase deviation is often described in power mismatch space. NDZ of methods based on disturbance injection is usually described in load parameter

3. Unintentional Islanding Issues

During unintentional islanding the safety of power line maintenance workers is a main cause of concern since the energized line from the excited DG is unknown to them after the grid is shut down. The voltage and the frequency attain values which are deviated fair enough from the nominal values of the EPS. If proper grounding techniques are not installed and initiated the magnitude of the damage caused will be much higher. Large mechanical torques and current are created in the generators or prime movers due to the instantaneous reclosing often known as out of phase reclosing. This scenario could also lead to transients that are potentially harmful in damaging the utility and other consumer equipments. In a lightly damped system the out of phase reclosing, will generate capacitive switching transient, which may lead to the crest over voltage approaching three times the rated voltage. Due to these reasons, early accurate detection and disconnection of the DG after the event of islanding is necessary. The main idea of detecting an islanding situation revolves around the monitoring of output parameters of the DG and its significant change which leads to proper justification of an electrical island occurred.

4. Islanding Detection Methods

4.1 Passive Methods

4.1.1. Under/over Voltage and Under/over Frequency (OUV/OUF)

The Under/Over Voltage and Under/Over frequency protection circuits are the fundamental detection schemes employed for terminating the inverter production into the utility grid. This detection is applicable when the voltage or frequency at the PCC is beyond the accepted limits. In the event of unintentional islanding taking place, there will be a significant power mismatch between the power consumed by the load and the inverter output power. The inverter is driven beyond its accepted limits for the detection of islanding. This method can be extensively used for reasons other than islanding also such as Line to Ground faults. Many advanced detection schemes rely on this method of detection for its inherent mechanism of detection and hence known as the fundamental detection scheme for islanding in grid connected DG systems. If the power mismatches between the inverter output and the power at the load are almost null, this method fails to detect, which is considered as the greatest weakness of this method. [1]-[6]

4.1.2. Voltage phase jump detection (PJD).

The phase difference between the inverter terminal voltage and its output current is measured and observed for sudden changes or jump.

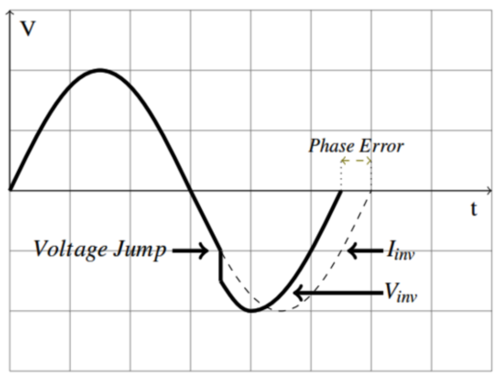

Fig. 4. Representation of voltage jump leading to phase error

The rapid change in the phase angle is the key to detect islanding in PJD. The Phase Locked Loop (PLL) is used to synchronize the inverter output current and the grid voltage during normal operation. When the phase errors exceed a preset value, the inverter is ceased from its operation. The Voltage PJD method can be applied to multi-inverter systems and the power quality issues are minimal in the grid side. Similar to the previous scheme, this method suffers from detection failures of islanding operation when the generated power is matched with the local load demands forming a large Non-Detection Zone (NDZ). The PJD method has a much smaller NDZ compared with the classical standard relay circuit methods[4,8].

4.1.3. Monitoring of voltage and current harmonics (VH).

The main sources of harmonics in a DG interfaced inverter are (1) Higher order harmonics produced due to switching, (2) Even harmonics due to dead time and semiconductor voltage drops, (3) Odd harmonics due to the ripple in the DC link voltage. A normal grid has the characteristic of low impedance which enables it to acquire and supply power to other devices connected to it. Even though compensation and control algorithms are embedded into the power system the voltage harmonics will be present in low magnitude satisfying the standards of harmonic distortion (THD<5%). When islanding occurs the grid is disconnected from the inverter module and the local load is immediately connected with the inverter. Since the local load has higher impedance compared with the grid, harmonic levels are also high which can be made as indicative figure for islanding detection. The primary indicators may be the THD of the voltage or the amplitude of 3rd, 5th, 7th, 9th and 11th harmonics. The main advantage of this method is that it is not dependant on power mismatches and hence the NDZ is very small compared to all other passive detection schemes. This method suffers from misinterpretation of an islanding event due to changes in the harmonic conditions triggered by sudden removal or addition of non-linear loads to the systems. [6, 10,17].

4.1.4. Rate of change of power output (ROCOP).

In the event of islanding there will be sudden power changes occurring in the DG interfaced inverter system. The change in power will be more during islanded operation since the DG supplies more power than the actual demand, compared to the power during normal operation of the system. A few sample cycles are taken for examination before any action is to be taken. If the values taken are beyond the threshold limits the inverter is made to shut down immediately. The method can quickly detect unsynchronized reconnection of the utility supply to a power island containing the DG unit [2].

4.1.5. Rate of change of frequency (ROCOF).

When the utility grid is disconnected from the inverter due to islanding, the inverter is driven to a state of changing its frequency. The change in frequency is due to the change in the passive components such as R, L and C from the grid to the local load. This change in frequency with respect to time is measured for a few cycles. The inverter shuts down if the rate of change of frequency exceeds a preset value. When frequency change rate exceeds the threshold for longer than the pre-set timedelay a ROCOF relay monitors the voltage waveform and trips up the circuit breaker. The detection speed of ROCOF is much larger than U/O voltage and U/O frequency methods. The main drawback of this method is that its inability to detect in the case of fluctuating and switching loads and are suitable only for stable loads. This method also has the drawback of not able to distinguish between islanding condition and sudden load changes. [2]

4.2 Active Methods

4.2.1. Active frequency drift (AFD).

In this method, the waveform of the current injected into the utility grid by the PV system is slightly distorted such that, when islanding occurs, the frequency at the PCC will drift up or down [24]. Due to the stability of the grid, the voltage and frequency at the PCC will not change. The distorted current wave when passed through a pure resistance the voltage across the resistive load is also distorted. The term distortion refers to the phase lag between the inverter output voltage and the voltage at the PCC. In the event of islanding taking place the utility grid is disconnected and the local load is connected to the inverter output. If the connected load is purely resistive in nature then the voltage response of this load is same as that of the current waveform which is distorted. The current response of the inverter advances itself and completes its cycle well ahead of the utility voltage by a time t . The inverter on the other hand detects this phase lag and indulges in a drift in frequency in its current response to make the phase lag to zero. DG operated grid connected inverters are designed to operate at unity power factor and hence the drift occurs. If the drift in frequency exceeds the threshold value set by the Under/Over frequency relays, islanding is detected. The major parameter describing the distortion of the inverter injected current is the chopping fraction (*cf*) [24], given by the following equation.

$$cf = \frac{2t_Z}{T_{Vutil}} \quad (1)$$

where tz is the dead zone time period and T_{Vutil} the time period for one cycle in the Utility voltage. The advantages of AFD methods are 1) it has a small NDZ compared to all other passive methods. 2) it is easy to install and the detection time is very less (less than 2s). The main weaknesses of AFD are 1) it can be operated only for purely resistive loads and for lightly inductive loads. NDZ are large for large valuesof C and L. 2) Also this method will fail to operate for multi-inverter systems. 3) since there is deliberate current distortion and injection into the utility grid, power quality issues are severe. Thus AFD schemes are applicable only for resistive loads and single inverter systems.

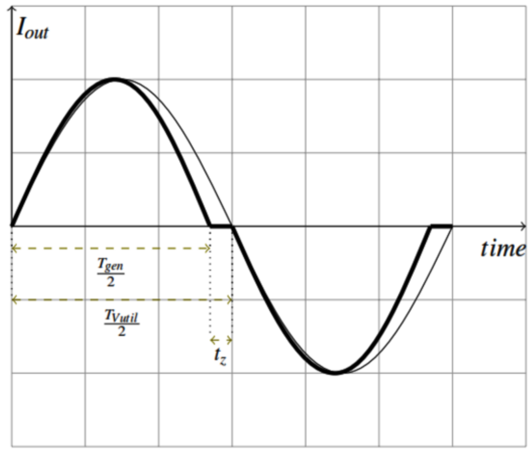

Fig. 5. Delayed current waveform compared with the PCC voltage

4.2.2. Active frequency drift with positive feedback (AFDPF).

The Active Frequency Drift with Positive feedback is a calibrated scheme of the AFD to overcome the drawbacks suffered by it in cases of multiinverter utility and loads with large value of L and C. The AFDPF uses a positive gain feedback which is the highlight of this method. This positive feedback increases the chopping fraction which leads to detection of frequency deviations of the utility load and the output current of the inverter with a higher rate with respect to time. At these higher rates of detection, islanding can be detected more quickly.

$$cf_k = cf_{k-1} + K(\Delta\omega_k) \quad (2)$$

cf_k = chopping fraction of the previous cycle *k* = frequency difference between previous cycle and present one. *K* = positive gain constant. The value of *cf* in AFDPF can be positive or negative. No matter if frequency drift is upward or downward, this method can reinforce the frequency drift instead of counteracting it, overcoming the impact of the load parameters [6, 25]. The advantages of AFDPF are that its capability to detect islanding more effectively than AFD technique for a wide variety of loads. The power quality is slightly affected due the distortions injected into the grid. The Vutil NDZ for high quality factor loads are still large in this technique. [11].

4.2.3. Sandia frequency shift (SFS).

The Sandia Frequency Shift is an extension of the AFD technique incorporating a positive feedback for the frequency of the inverter output voltage. This feedback is accounted for through the chopping fraction parameter given by,

$$cf = cf_0 + K(f_{PCC} - f_{grid}) \tag{3}$$

Where *cf* is the chopping fraction with no deviation in frequency, *K* is the accelerating gain, f_{PCC} is the frequency of voltage at the PCC, and f_{grid} is the frequency of the grid. During normal operation of the grid connected DG interface, this technique tries to change the frequency of the PCC voltage. Due to grid stability this attempt goes in vain. But when the grid is disconnected during unintentional islanding the frequency of voltage at the PCC increases which leads to increase in the chopping fraction. This increase further leads the grid inverter frequency to increase and to detect islanding when the threshold limits are crossed. The detection time of SFS is within 0.7 s, and it even can detect islanding within 10 cycles of operation. The NDZ is less compared to AFD and AFDPF methods and the presence of power quality issues is also less. [12, 16]

4.2.4. Sandia voltage shift (SVS).

Sandia voltage shift is similar to SFS in principle. By applying a positive feedback to the amplitude of voltage in PCC, the inverter changes its current output and power output. When connected to main grid, the amplitude of voltage is not affected by power change, whereas without the support of main grid, power output changes can accelerate the voltage drift to detect islanding [6]. SVS is easy to implement, and it has the same efciency as the SFS method which is based on positive feedback. The primary weakness of SVS is that it slightly degrades power quality. Secondly, because of changing the inverter’s output power, it affects the maximum power point tracking algorithm of the inverter, reducing the inverter’s operating efficiency [6].

4.2.5. Impedance measurement (IM).

This method detects the changes in impedance during grid disconnection in the output of the inverter. The change in impedance is calculated by the rate of change of voltage to current of the inverter. During islanding operation the voltage varies with respect to the current and it is monitored from the inverter side. This equivalent impedanceseen from the inverter can be used to detect islanding. The detection time is well below the standards (less than1 s) for a single DG system and the NDZ is also small compared to some active methods. In case of multiple inverters unless and until all the inverters operate synchronously the detection will not be effective. Also it is very tedious to obtain the exact value of grid impedance to be set for the threshold value since it is highly intermittent. [9]

4.2.6. Sliding mode frequency shift (SMS).

The positive feedback mechanism can be implemented for the amplitude, frequency and the phase at the PCC. The positive feedback mechanism is applied to the phase of the voltage at the PCC in this method. During normal operation of the grid the power factor is almost maintained to be unity by the inverter. Hence there is no phase difference between the inverter output current and PCC voltage. A SMS curve is given by the following equation

$$\theta = \theta_m \sin\left[\frac{\pi}{2}\frac{f^{k-1} - f_n}{f_m - f_n}\right] \tag{4}$$

In Eqn.4 θ_m is referred as maximum phase shift occuring at frequency f_m. f_n is the rated frequency and f^{k-1} is the frequency at the previous cycle.

The slope of a SMS curve is greater than that of a load in the unstable region as shown in Fig 6. In SMS method the phase angle between the current and voltage of the inverter is mathematically equated to form a function of the frequency of V_{PCC} (Voltage at Point of Common Coupling). During islanding operation, the phase angle of the local load and the frequency will vary according with the SMS curve. Over a period of time this frequency deviation exceeds the threshold frequency limits which is detected by the Over/Under frequency relay and thus islanding can be detected. The main strength of the SMS method is that it is easy to implement and has a smaller NDZ compared to other active methods with a detection time less than 0.5s. It is also observed in multiple inverter systems the SMS is highly effective in terms of system reliability. Poor transient stability and reduced grid power quality are the main weaknesses of this method. [8]

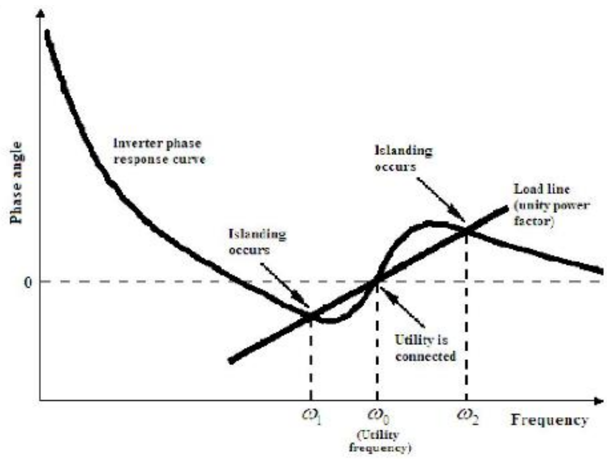

Fig. 6. Operation of Slip-Mode frequency Shift method, as in [8]

4.3. Communication Based Methods

4.3.1. Power line carrier communication (PLCC).

In PLCC method a communication channel is used to transmit signals on the event of grid failure/shutdown (islanding) to the grid connected DG units, following which the DG inverters are shut down. In this method transmitters are installed at the grid terminal which uses the power line for communication. The receiver is installed at the DG unit. A suitable frequency of signal is set as the indicator for islanding event. The detection time is about 200 ms [6]. The NDZ is practically zero in this method for loads in the normal range. Also the power quality is not affected since there is no injection of current into the power system utility as in the case of Active methods. The grid transient response is good for single as well as for multi inverter systems. The weaknesses of this method are its cost involved in installing transmitter and receivers and are not viable for low density DG systems. [13, 14, 18]

4.3.2. Signal produced by disconnect (SPD).

The similarity between PLCC method and SPD method is the type of communication network adopted for signal transmission. The SPD method differs by the type of signal used viz., microwave, telephone line and other forms. To prevent the failure caused by generator, channel or receiver, this method also utilizes the consecutive carrier signal [6]. The SPD method practically has no NDZ, and has an additional feature which allows con- trol of DG by main grid, which would be beneficial. This coordination helps in improving the starting characteristicsof the system. Large capital investment is needed for installation of transmitters, receivers, wiring, repeaters (for microwave transmission) and setting up of communication protocol which makes this method unsuitable for low power density DG units. [13, 14]

4.3.3. Supervisory control and data acquisition (SCADA).

In this method state of circuit breakers are monitored in the main grid through highly integrated communication systems. The Energy Control Centre (ECC) where the SCADA system is installed, continuously monitors the power system for a local area covering upto 50 kms in radius. In the event of islanding taking place, the trip signal is sent to the corresponding circuit breakers to disconnect the DG from supplying power. The NDZ for this method will be zero if the system is properly integrated with efficient communication channels. In case of a busy system the monitoring speed may be slow enough to detect the event of islanding which makes it a huge drawback for this method. Also the investment involved is large. [13, 14]

4.4. Signal Processing Based Methods

4.4.1. Pattern Recognition.

This technique mainly relies on signal feature extraction from a finite poll of pre-simulated data collected from DGs. A classification technique known as Random Forest (RF) classifier is used to distinguish the islanding and non-islanding situations. The features of voltage and the current waveforms at the PCC during islanded and nonislanded cases are taken into consideration for analysis. These simulations and data are generated using the standard IEEE 34 bus system for training and testing this method. The results from the RF classifier proves to be the best in terms of small NDZ and elimination of nuisance tripping when compared with other classifier techniques viz., Nave Bayesian classifier, Support Vector Machine Classifier, Decision Tree and Neural Network Classifier. [19].

4.4.2. Wavelet Analysis.

Wavelets are functions, used to efficiently describe a signal by decomposing it into its constituents at different frequency bands which makes it suitable for several power system applications and its analysis such as feature extraction, de-noising and data compression of power quality waveforms. Wavelet based Islanding Detection may be concatenated to an existing passive islanding detection method for reducing the NDZ prevailing due to the passive method. The spectral changes occurring at the frequency of voltage at the PCC are detected using Wavelet analysis. These changes are not detectable in passive detection methods. It is possible using the Wavelet analysis to extract features of the islanded and non-islanded conditions without injecting any current or high frequency signal into the EPS which makes it more reliable and robust since there are no power quality degradation issues as in the case of Active islanding detection methods. Several wavelet transformation techniques are available and the NDZ is highly reduced even in the case of power mismatches almost equal to zero. [20, 21].

4.4.3. Signal Correlation technique.

In this technique a negligible amount of reactive current (smaller than 5%) is injected into the rated current component and the signal cross-correlation is estimated using the power frequency deviation as the second signal for analysis. The cross-correlation index is estimated using the signal correlation tool and the results throw light upon the event of islanding or normal operation. Islanding occurs for a Cross-correlation index value larger than 0.5. The advantage of this method is that the power quality degradation is minimized due to low percentage injection of reactive current. In case of multiple DG systems the cumulative effects of injected reactive currents may lead to degradation of power quality. [22, 23].

5. Comparison And Discussions

The summary of the various IDMs and their performances with respect to detection time, size of Non Detection Zone, power quality disturbances, system cost and operation under multiple DG units is given in Table1. It is evident that to mitigate the size of NDZ there has to be a trade off between system cost and power quality issues. More the cost, more the reliability of the IDM. When materializing communication based IDMs, the span of control should be large enough such that multiple DGs are benefited out of the detection scheme. It should be primarily aimed at implementing in a city, district or even a country. On the other hand for low power density DGs, the Active IDMs will be more cost effective and reliable. It would be beneficial if the passive methods together with the Sinal Processing methods forming a Hybrid Detection scheme would be most suitable for reliable and robust operation. Active IDMs will emerge as the most preferred IDM among those who have installed grid connected PV systems in their residence in the next decade due to its ability to detect islanding at a faster rate than passive methods and its cost effectiveness.

Table 1. Comparison of Various Islanding Detection Methods

Detection time	Type and Class of IDM	NDZ	Power Quality	System Cost	Operation under Multi DG units
Large	OUV/OUF (Passive)	Very Large	No Impact	Low	Possible
Average	PJD (Passive)	Large	No Impact	Low	Possible
Average	VH (Passive)	Average	No Impact	Low	Possible
Average	ROCOP (Passive)	Medium	No Impact	Low	Possible
Average	ROCOF (Passive)	Small	No Impact	Low	Possible
Small	AFD (Active)	Small	Slight Degrade	High	Complex
Small	AFDPF (Active)	Average	Slight Degrade	High	Complex
Small	SFS (Active)	Small	Slight Degrade	Medium	Complex
Small	SVS (Active)	Small	Slight Degrade	Medium	Complex
Small	IM (Active)	Small	Slight Degrade	High	Complex
Small	SMS (Active)	VerySmall	Slight Degrade	High	Complex
Very Small	PLCC (Communication)	Very Small	No Impact	Very High	Possible
Very Small	SPD (Communication)	None	No Impact	Very High	Possible
Very Small	SCADA (Communication)	None	No Impact	Very High	Possible
Very Small	Pattern Recognition (SP)	Very Small	No Impact	Medium	-
Very Small	Wavelets (SP)	Very Small	No Impact	Medium	-
Very Small	Signal Correlation (SP)	Very Small	Mild Impact	Medium	-

6. Conclusion

This paper enunciates and compares different islanding detection techniques with their attributes and cons for each method. In modern EPSs with several DGs having significantly high levels of penetration, it is important to exploit the power wastages using skillful and contemporary mechanisms. Power quality issues are always allied with the detection time of any method. It is essential to have a proper tradeoff between quick detection time with minimal power quality issues.

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