Survey of Photovoltaic Power Systems Islanding Detection Methods

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***Abstract*-Distributed generators (DG), such as photovoltaic cells, are low cost, highly reliable and have electronic interfaces and reduced emissions. Even with the mentioned benefits, there are technical limits on the degree to which DG can be connected. One of these technical concerns is the islanding phenomenon. In utility practice at the present time, accidental islanding is an undesirable mode of operation and is not permitted. Therefore, islanding must be detected and the islanded DG units must be disconnected from the rest of the system. This paper presents a survey of the islanding detection methods for grid-connected photovoltaic (PV) systems.**

Index Terms—islanding, distributed generation, photovoltaic power systems

I. Introduction

Distributed Power Generation Systems (DPGS) based on alternative energy are more and more contributing to the energy production everywhere around the world. These DPGS have been gaining popularity due to their higher efficiencies and lower emissions, and the technologies have already been used to [1]:

- Share peak generation during peak load hours when the cost of electricity is high
- Provide standby generation during system outages.

The DG, such as photovoltaic cells, fuel cells, wind turbines, and microturbines, are low cost, low voltage, highly reliable and have electronic interfaces and reduced emissions.

Even with the mentioned benefits that DPGS can provide, there are technical limits on the degree to which DPGS can be connected. Boundaries of operation for both voltage and frequency are specified in order to protect both the utility and the generation system [1, 3, 4, 5]. In the case when these boundaries are exceeded, the distribution system should cease to energize the utility network.

Another of the technical concerns associated with the proliferation of DPGS units is the islanding phenomenon. An island is formed when one or more DPGS units and an aggregate of local loads are disconnected (islanded) from the main grid and remain operational as an islanded (autonomous) entity [3, 6, 7, 8, 9]. Islanding is either due to preplanned (intentional) events or due to accidental (un-intentional) events. In utility practice at the present time, accidental islanding is an undesirable mode of operation and not permitted. Therefore, islanding must be detected and the islanded DPGS units must be disconnected from the rest of the system.

This paper presents a survey of islanding detection methods for grid-connected photovoltaic (PV) systems. Five methods: passive inverter resident methods, active inverter-resident methods, communication-based methods, a method at the utility level, and hybrids methods; are summarized.

II. The Islanding Concept

Islanding of grid-connected PV systems occurs if the PV system continues to energize a section of the utility grid, after that section has been disconnected from the main utility voltage source [3, 6, 7, 8]. Unintentional islanding can cause problems with safety, power quality, and reliability [10]. Because of this, unintentional islanding detection is required by standards such as IEEE 929-2000, IEEE 1547, and UL 1741.

Consider the system configuration shown in Fig. 1. The node PCC is the Point of Common Coupling defined as the point at which the electric utility and the customer interface occurs [3]. This DG system is islanding when the PV system continues to energize the components to the left of the recloser after the recloser has been opened.

Unintentional islanding operation is potentially undesirable both from the safety point of view – where a circuit may be assumed to be de-energized when it is not, and from the point of view of power quality – where the standards normally guaranteed to customers may not be met.

Unintentional islanding detection schemes may be divided into five categories: passive inverter-resident methods, active inverter-resident methods, communications-based methods between the utility and the inverter, methods at the utility level, and hybrids methods.

III. Passive inverter-resident methods

Passive inverter-resident methods rely on the detection of an abnormality in the voltage amplitude, frequency or phase at the PCC between the inverter and the utility when the island is created [11, 12, 13].

A. Under/over Voltage and Under/over Frequency

All grid-connected PV inverters have U/O V/F protection methods that cause the inverter to stop supplying power to the utility grid if the frequency or voltage at the PCC is outside of prescribed limits. These protection methods serve as islanding detection methods because the voltage or frequency will shift if there is a mismatch between the inverter output power and the power consumption.

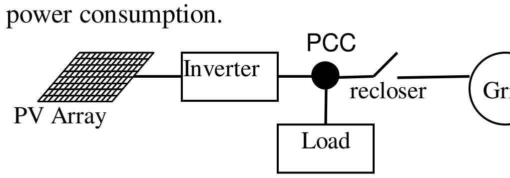

Fig. 1. System configuration

If the voltage or frequency shift drives the inverter to its detection limits, the inverter shuts down and the island has been detected [6, 14, 15, 16, 17, 18, 19].

Some of the strengths of this method are that this method is required for several reasons other than islanding detection and some of the other islanding detection methods rely on this method to detect the island. Its greater weakness is that this method fails to detect the island if the power (real and/or reactive) at the load is close to the power supplied by the inverter.

B. Voltage Phase Jump Detection

Phase jump detection (PJD) involves monitoring the phase difference between the inverter's terminal voltage and its output current for sudden changes [4, 19, 20, 21, 22, 23]. A sudden change indicates that the voltage at the inverter terminals is no longer sustained and it has shifted in phase to match the phase angle of the local load. If this phase error is greater than some threshold value, the controller can de-energize or shut down the inverter.

Among its strengths we can find that this method is easy to implement because all that is required is to modify the phase lock loop (PLL) required by the inverters for utility synchronization. What is required is to add the capability to deactivate the inverter when the phase error exceeds some threshold. Also, this method does not affect the power quality of the inverter and can be used with multiple inverters systems. Unfortunately, this method is not easy to implement because it is difficult to determine the correct threshold that provides reliable islanding detection but does not result in nuisance trips. Also, it has a relatively large non detection zone (NDZ), and certain loads can cause transient phase jumps that can cause nuisance trips of the inverter.

C. Detection of Harmonics (DH)

With this method, the inverter controller monitors the total harmonic distortion (THD) of the inverter terminal voltage and shuts down the inverter if the THD exceeds a threshold [24, 25]. When the island is formed, the harmonic currents produced by the inverter will flow into the load, which has much higher impedance than the utility. The harmonic currents interacting with the larger load impedance will produce larger harmonics in the PCC. These THD can be detected by the inverter, which can then assume that the DG inverter is islanding [13, 17, 19, 26].

This method has the advantage that it does not have a non-detection zone when the local load matches the inverter output power. However, with this method it is not always possible to select a trip threshold that provides reliable islanding protection but does not lead to nuisance tripping of the inverter; also the method cannot be used when multiple inverters are connected to the island.

IV. Active Methods Resident in the Inverter

Active inverter-resident methods use a variety of methods to attempt to cause an abnormal condition in the PCC voltage that can be monitored to detect islanding [27]. When the utility grid is connected, the stability of the grid prevents changes in amplitude, frequency, and/or phase. When the subsystem is islanded, these voltage, current or frequency disturbances that are injected into the supply system will perturb the load circuit. Islanding conditions are thereby detected if the disturbances have caused a change in voltage, current or frequency at the PCC [11, 12, 13].

A. Impedance Measurement

Impedance measurement techniques attempt to detect the change in inverter output circuit impedance that occurs when the low impedance distribution network is disconnected [5, 20, 25, 28, 29, 30, 31]. The DG inverter appears to the utility as a current source supplying current given by:

$$i_{DG-inv} = I_{DG-inv} \sin(\omega_{DG} t + \phi_{DG}) \qquad (1)$$

The output power is changed by perturbing the inverter's output current amplitude (I_{DG-inv}) and monitors the change in output voltage that results. Since it is monitoring dv/di , it is effectively measuring the load circuit impedance [21].

The primary advantage of the impedance measurement method is its extremely small NDZ. This method has many weaknesses. The first one is that its effectiveness decreases in the multi-inverter case unless all the inverters using this method are somehow synchronized. In addition, it is necessary to set an impedance threshold, below which the impedance detection method assumes that the grid is still connected. Thus, this method is impractical because a precise value of grid impedance that is not known is required.

B. Signal injection

Using this method the inverter injects a known signal into the output current and monitors the terminal voltage response [19, 25, 32]. One signal that can be injected is a current harmonic of a specific frequency different than the line frequency.

This method does not have a non-detection zone when the local load matches the inverter output power. However, it is not always possible to select a trip threshold that provides reliable islanding protection but does not lead to nuisance tripping of the DG inverter. Also, multiple inverters injecting the same signal may cause false trips or otherwise interfere with each other.

C. Load insertion

When the recloser is opened the inverter can connect load impedance across its output terminals and monitor changes that occur [20, 21]. For example, a capacitor can be inserted across the output, as shown in Fig. 2 [33].

This method is resistant to false trips caused by random phase jumps in the grid voltage. There are concerns about interference among multiple units and the ability to reliably detect impedance changes with practical values of the inserted load.

D. Sliding Mode Frequency Shift

The principle of the sliding mode frequency shift (SMS) method is to force the frequency of inverter output up/down by controlling the starting phase angle of the inverter current [6, 10, 13, 15, 34].

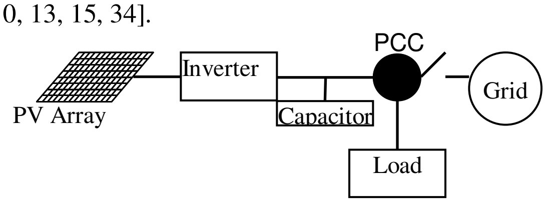

Fig. 2. System configuration

In the SMS method, the current-voltage phase angle of the inverter, instead of always being controlled to be zero, is made to be a function of the frequency of the voltage at the PCC [14, 22, 35, 36, 38] as shown in Fig. 3.

This method is relatively easy to implement, since it involves only a slight modification of a component that is already required, the PLL. Also, this method has a small NDZ when it is compared to other active methods. The method is effective in the multiple inverter applications and provides a good compromise between islanding detection effectiveness, output power quality, and impact on the transient response of the overall power system. However, SMS requires a decrease in the output power quality of the DG inverter.

E. Active Frequency Drift

The principle of the active frequency drift (AFD) or frequency bias method is to force the frequency of inverter output up/down by using positive feedback to accelerate the frequency of the inverter current [6, 10, 15, 39]. In this method, by injecting into the PCC a current waveform that is slightly distorted changes the frequency [13, 36, 37, 38]. Fig. 4 shows an example of a DG inverter output current waveform that implements upward AFD.

The ratio of the zero time t_z to half of the period of the voltage waveform, $T_{Vutil}/2$, is referred to as the chopping fraction (*cf*):

$$cf = \frac{2t_z}{T_{Vutil}} \qquad (2)$$

This method is easy to implement in a DG inverter with a microprocessor-based controller and can be used in the multiple-inverter case. However, AFD requires a small degradation of the DG inverter output power quality and has a NDZ that depends on the value of the chopping fraction.

F. Sandia Frequency Shift

Sandia Frequency Shift (SFS) or Active Frequency Drift with Positive Feedback implements positive feedback by making the chopping fraction to be a function of the error in the line frequency [10, 33, 40, 41]:

$$cf = cf_o + K\left(f_a - f_{line}\right) \qquad (3)$$

If the chopping fraction increases the PV inverter frequency increases and the over frequency relay shuts-down the inverter.This method has one of the smallest NDZs of all the active islanding detection methods, does not lose effectiveness in the multiple inverter case if all inverters in an island use the same scheme, and can be extremely effective if it is implemented in combination with the Sandia Voltage Shift (SVS) islanding detection method. However, with this method the output power quality of the DG inverter is reduced slightly because of the positive feedback. Also, this method is usually stimulated by noise or harmonics on the reference waveform.

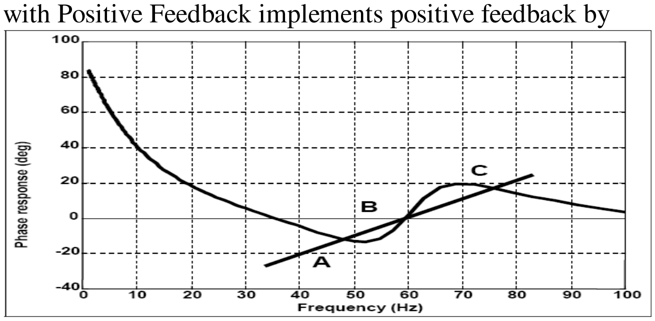

Fig. 3. Phase Angle vs. Frequency [14]

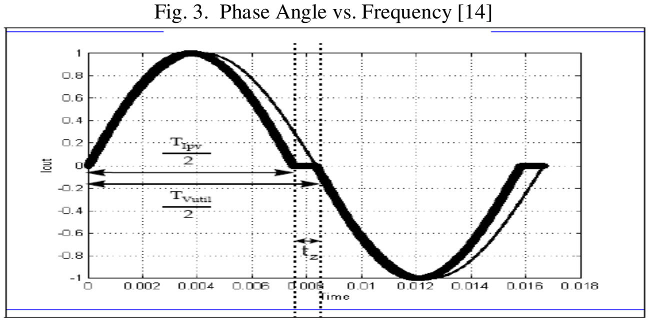

Fig. 4. Example of a distorted Waveform [14]

G. Frequency Jump

In this method, dead zones are inserted into the output current waveform, but not in every cycle. Instead, the frequency is dithered according to a pre-assigned pattern [17, 27]. When disconnected from the utility grid, the island is detected by forcing a deviation in frequency, as in the frequency bias method or by enabling the inverter to detect a variation in the PCC voltage frequency that matches the dithering pattern used by the inverter.

The primary strength of this method is that if the pattern is sufficiently sophisticated, the method can be relatively effective in islanding detection when used with single inverters. Also, this method should have almost no NDZ in the single-inverter case. Its primary weakness is that it loses effectiveness in the multiple inverter case unless the dithering of the frequency is somehow synchronized.

H. Unstable Frequency Trip

This method implements a *df/dt* computation on a cycle-by-cycle basis [33, 43, 42]. Then, this result is compared with a frequency rate threshold and the inverter is shuts down if the *df/dt* exceeds this threshold.

This method complements SFS and can be used in the multiple inverter case. A problem of this method is that there appeared to be nuisance tripping due to the highly sensitive setting. This method suffers from a serious implementation difficulty in that it is difficult to choose thresholds that provide reliable islanding detection but do not result in frequent nuisance trips.

I. Sandia Voltage Shift

Sandia Voltage Shift (SVS) applies positive feedback to the current or active power regulation control loop of the inverter to cause the inverter terminal voltage to rapidly shift to the under/over voltage detection threshold if the distribution network is not present to maintain the voltage [5, 44]. The positive feedback introduces instability that drives the inverter terminal voltage towards one of the voltage limits.

This method is easy to implement using a micro-controller and when implemented with SFS, this method presents a small NDZ. A weakness of this method is that it requires a very small reduction in output power quality. Because of this, penetration levels of inverters using the method may have to be kept low.

J. General Electric Frequency Schemes (GEFS)

The methods are based on injecting a disturbance into the system through the DQ-frame current controllers, and monitoring the disturbance impact at the PCC [15, 16]. There are two key concepts in the DQ implementation. First, the active power is proportional to the D axis components; second, the reactive power is proportional to the Q-axis components, as shown in Fig. 5.

This method is easy to implement with a microprocessor, has no NDZ, has negligible power-quality impact, has minimal implementation cost (software code only), and is very robust to grid disturbances. However, injection of the disturbance signal to the system demands special conditions for both the disturbance signal frequency and the amplitude and the magnitude of the disturbance signal should be as small as possible.

V. Communications-based Methods

Communications-based methods involve a transmission of data between the inverter and utility systems, and the data is used by the PV system to determine when to cease or continue operation [11, 45, 46, 47].

A. Power line carrier communications

Fig. 6 shows an example of a system configuration that includes a power line carrier method for islanding detection.

To detect the unintentional islanding, the power line is tested for continuity by sending a signal by the transmitter (T). When the PLCC signal is lost the receiver (R) can command the inverter(s) to cease operation, or it can open its own switch to isolate the PV inverter and load from the PCC [20, 24, 25, 48].

This method has multiple strengths: it does not have an NDZ, the DG inverter's output power quality is not degraded, the number of inverters on the system does not affect its performance, and would be effective at any penetration level. However, if a load inside the island can replicate the PLCC signal it would be possible for the PLCC-detecting device to detect this signal instead and fails to detect the unintentional islanding. Also, the cost of the receiver and transmitter can be too high.

B. Signal Produced by Disconnect

With this method the utility recloser is equipped with a transmitter as is shown in Fig. 7. This transmitter sends a shut down signal to the inverter when the recloser is opened [14].

This method allows control of the DG system by the utility, resulting in coordination between the system and the utility. Also, this method presents no NDZ and can be used with multiple case-inverters.

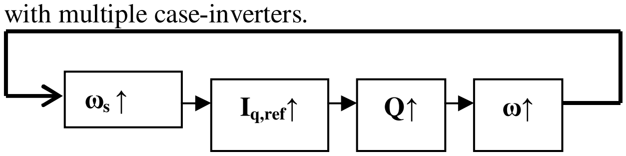

Fig. 5. Feedback in DQ implementation

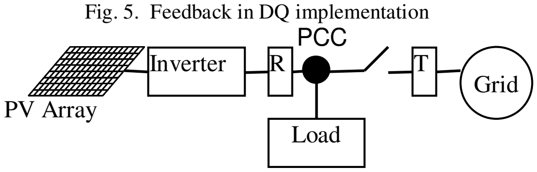

Fig. 6. System configuration including

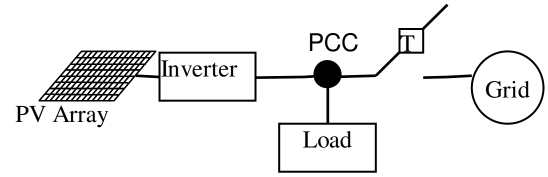

Fig.7. System configuration

On the other hand, each inverter in the potential island will require additional wiring, which makes this method relatively expensive and involves significant permitting and design complications.

C. Supervisory Control and Data Acquisition

The principle of the supervisory control and data acquisition (SCADA) to detect unintentional islanding is to monitor states of entire distribution system such as voltage, frequency and other characteristics [8, 25, 49]. This information is then sent through communication links to a central station. After the utility is disconnected, if the parameter (voltage or frequency) can still be detected from the disconnected area, then the occurrence of islanding is hereby detected.

If the system is properly instrumented and controlled, this method is highly effective to detect unintentional islanding and the NDZ is eliminated. However, cost of implementation is highly expensive because each inverter installed needs separate instrumentation and communication equipment to send necessary information to a central station.

D. Transfer Trip Scheme

The basic idea of transfer trip scheme (TTS) is to monitor the status of all circuit breakers and reclosers that could island a DG system. When a switching operation produces a disconnection to the substation, a central algorithm determines the islanded areas. A signal is then sent to trip inverter in the unintentional islanded areas [25]. Fig. 8 illustrates the basic idea of this scheme.

Utility companies have years of experience with this scheme for various protection applications so it can be easily accepted. This method would allow additional control of the distributed generators by the utility, increasing the coordination between distributed generators and utility resources. The same system can also be used to provide a signal for reconnecting DG units after fault clearance.

Its main disadvantages are the cost and potential complexity because signal transmitters are needed for all possible disconnecting points in the system.

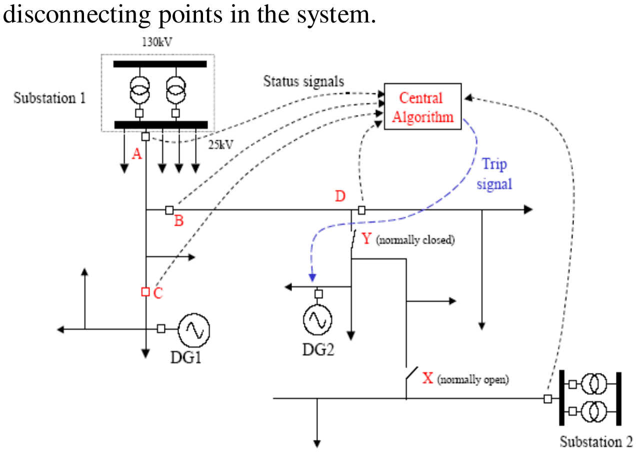

Fig. 8. Transfer trip scheme [25]

If there are many reclosers and the feeder topology varies, a transfer trip scheme can become quite complicated.

VI. Method at the Utility Level

The methods at the utility level also actively attempt to create an abnormal PCC voltage when the utility is disconnected, but the action is taken on the utility side of the PCC [11].

A. Impedance Insertion

The principle of the impedance insertion is to connect low-value impedance, such as a capacitor bank, to a distribution feeder as shown in Fig. 9 [50].

With this method, when the recloser is opened the sudden addition of the impedance will imbalance the reactive power requirement, causing a frequency decrease which the under frequency relay can detect.

This method offers several advantages: capacitors of this type are readily available, and utilities have a great deal of experience with them; it can be used in multiple-case inverters, and presents no NDZ. However, the capacitors needed add a great deal of expense to the DG system and it is unclear which party would be responsible for the expense of this bank.

VII. Hybrid Detection Methods

Reference [51] presents a hybrid detection method which can detect the islanding condition from local measurements of PCC voltage and current signals, typical of passive methods, but evaluates the high-frequency components injected by the PV DG inverter to reveal the islanding condition in a similar way as done by active methods.

A novel islanding detection method is proposed in [52, 53]. With this method, the inverter acts as a virtual inductor as the frequency is slightly higher than the fundamental frequency of the normal utility. When power failure occurs, the amplitude or frequency of load voltage changes and the islanding operation can be detected.

A method that uses a synchronous reference frame (DQ0) phase-locked loop (PLL) to implement a quasiactive islanding detection scheme is presented in [54]. This technique, accompanied with nothing more than the standard OVP/UVP, OFP/UFP terms, allows for increased performance in passive detection and a minimization, with elimination of the NDZs experienced by the system.

Because it is difficult to choose the gain of the positive feedback in SMS, AFD and SFS algorithms, in [54] is presented an algorithm that is a hybrid of both passive and active islanding detection methods. The algorithm presented uses a covariance index as a passive indicator to activate the active islanding detection method. The active method causes power shift action which can vary the output reactive power of the PV system to realize the islanding detection.

A novel hidden gene concept that combines the merits of passive and active approaches is introduced in [55].

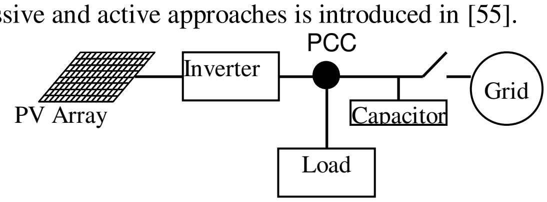

Fig. 9. System configuration

A moving averaging filter is embedded into the inverter's modulation frequency controller as a hidden gene. This hidden gene will not express itself in grid-connected situation because of the dominance of the grid. However, any tiny frequency disturbance during the transition from grid-connected operation to islanding operation will prompt hidden gene to express itself distinctly, providing a marked indicator of islanding.

A technique based on positive feedback (PF) (active technique) and voltage imbalance (VU) (passive technique) is presented in [56]. The main idea is to monitor the three-phase voltages continuously to determinate VU. If the VU is above the set value, frequency set point of the DG will be changed. The system frequency will change if the DG has been islanded.

VIII. Conclusion

Several islanding detection techniques have been presented. They can be mainly classified in five groups: passive inverter resident methods, active inverter-resident methods, methods at the utility level, communications-based methods between the utility and PV inverter, and hybrids methods.

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