디지털 록인 앰프를 이용한 새로운 하이브리드 방식의 단독운전 검출법

A Novel Hybrid Islanding Detection Method Using Digital Lock-In Amplifier

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ABSTRACT

Islanding detection is one of the most important issues for the distributed generation (DG) systems connected to the power grid. The conventional passive islanding detection methods inherently have a non-detection zone (NDZ), and active islanding detection methods may deteriorate the power quality of a power system. This paper proposes a novel hybrid islanding detection method based on Digital Lock-In Amplifier with no NDZ by monitoring the harmonics present in the grid. Proposed method detects islanding by passively monitoring the grid voltage harmonics and verify it by injecting small perturbation for only three-line cycles. Unlike FFT for the harmonic extraction, DLA HC have lower computational burden, moreover, DLA can monitor harmonic in real time, whereas, FFT has certain propagation delay. The simulation results are presented to highlight the effectiveness of the proposed technique. In order to prove the performance of the proposed method it is compared with several passive islanding detection methods. The experimental results confirm that the proposed method exhibits outstanding performance as compared to the conventional methods.

1. Introduction

The growth of distributed power generation systems (DPGSs) presents an efficient and economical way of generating power near the load(s). DPGS incorporating the renewable energy sources like photovoltaic, fuel cells, ESS etc. are able to provide power to local loads as well as inject surplus power into the grid [1].

Besides the several advantages there are safety concerns regarding interconnection of DPGS with grid. One of the most important phenomena regarding interconnection is “Islanding” The phenomenon of “islanding” in a DPGS is an electrical phenomenon, which occurs when the energy supplied by the grid is interrupted due to grid fault DPGS continue to energize the local loads. Thus, forming an ‘island’, which contains both local loads and generation, so that security, restoration of service, reliability of the equipment, safety of personnel involved, and the power grid restoration may be compromised. Therefore, in case of an island formation DPGS should disconnect themselves from the grid within 2s as defined IEEE Std. 1547.

Owing to the importance of islanding detection, considerable work has been published in literature, which can be divided into two main categories as shown in Fig. 1, 1) Remote detection and 2) Local Detection, latter can be further classified into three types a) Active b) Passive and c) Hybrid detection methods. Remote Islanding detection are based on communication between DPGSs and the power utilities. However, in terms of implementation the remote detection techniques methods are complex, inflexible, expensive and thus uneconomical.

Passive algorithms monitor system parameters of DGPS, such as voltage, frequency, phase etc [1]. During Islanding Phenomenon, when power mismatch between DGPS and local loads is negligible, deviation of system parameters is not enough. Therefore, in low power mismatch case passive methods suffers with the phenomenon of “non-detection zone” (NDZ). The NDZ is defined as the range (in terms of the power difference between the DPGS and the local loads) in which an islanding detection technique fails to detect this condition. The main disadvantage that can be concluded in case of conventional passive methods is a significant non-detection zone (NDZ).

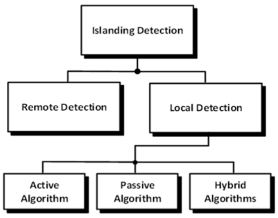


Fig. 1 Islanding Detection algorithms classification

Active islanding detection techniques intentionally introduce the disturbance at the output of DPGSs under a controlled manner [2]. Although, active techniques have the advantage of reducing or even eliminating the NDZ, to achieve that, they may deteriorate the quality of the power injected to the grid or even cause instability.

Owing to large NDZ of passive techniques, and constant power deteriorating of the active techniques, this paper presents the hybrid islanding detection which is equipped with advantages of both active and passive method. Proposed method detects 5th and 7th harmonics at the Point of Common Coupling (PCC) in real time using Digital Lock-In Amplifier (DLA). In case of islanding, variation in the harmonic amplitudes occurs, hence potential islanding condition is suspected, which is verified by injecting non-characteristics harmonic perturbation for three-line cycles. Since the harmonic characteristics are not dependent on the load conditions, thus proposed technique does not have any NDZ. Moreover, small harmonic perturbation is injected for only three lines cycles, therefore the output power quality is not deteriorated at all. The key features of the proposed islanding detection techniques include: 1) Proposed method does not require any additional hardware it only requires PCC voltage feedback. Moreover, 2) it is independent of type of current controller or PLL, hence making it compatible with any controller scheme. 3) Proposed method control parameters are easy to implement because it contains only LPF and multiplier. 4) DLA harmonic extraction is generalized, and it is capable to calculate any nth order harmonic. 5) DLA is immune to any kind of DC offset, high frequency noise and other measurements errors which can arise due to feedback sensor inaccuracies. Next section will explain the working principle of the proposed method in detail.

2. The Proposed Islanding Detection Technique

Fig. 2. shows the system under study, where grid connected inverter is connected to the PCC through LCL filter, loads are connected in parallel with the grid and inverter. Switch ‘S’ is controlled by the inverter main control, however in case of grid fault, trip signal must be generated to turn off the switch ‘S’ to prevent island formation.

2.1 Digital Lock-In Working Principle

Digital Lock-in Amplifiers (DLA), also known as Phase-Sensitive Detectors (PSD), are widely used in physical

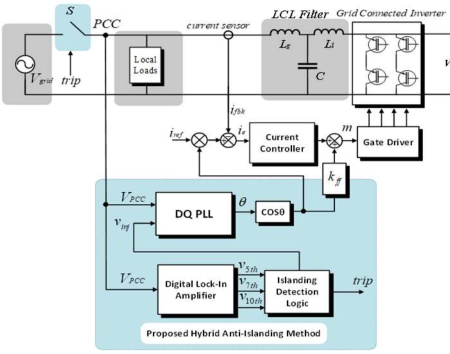


Fig. 2 Proposed Islanding Detection Method

instrumentation for the extraction of low-magnitude periodic signals buried in random noise and other disturbances. Fig. 2(a) shows the general structure of the DLA, it works on the principle of multiplying the input signal with the reference signal with a fixed frequency i.e. Fig. 1 (a). Amplitude information of desired frequency can be extracted from signal containing multiple frequencies. This process is also termed as Phase Sensitive Detection (PSD), down-modulation or down-mixing.

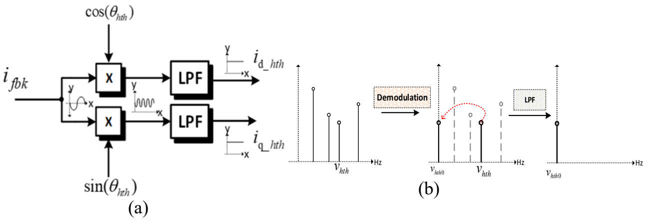
DLA outputs have two characteristics, 1) when fixed frequency pure sinusoid reference signals with arbitrary phase are multiplied to the input signal, the amplitude and phase information of the desired harmonic present in the input signal is shifted or converted to zero frequency i.e. DC value as shown in Fig 3. (b), Moreover, the other harmonics present in the input signals which can be considered as noise are shifted to their respective double frequency component. Simply, amplitude information of any desired harmonic of the grid voltage signal can be extracted by means of the DLA. Following equations explain the harmonic extraction in detail.

$$V_{grid} = v_p \begin{pmatrix} \cos\left(\omega_g t + \theta_g\right) + v_{3h}\cos\left(3\omega_g t + 3\theta_g\right) \\ + \ldots + v_{nh}\cos\left(n\omega_g t + n\theta_g\right) \end{pmatrix} \tag{1}$$

Eq. (1) shows the characteristics equation for the grid voltage which contains characteristics odd harmonics up to n^{th} order. Whereas, v_{nh} represents the peak amplitude of the n_{th} harmonic. θ_g represents the grid phase angle.

$$\begin{aligned} v_{x_{hth}} &= v_{grid} * \mathrm{v}_{\mathrm{hth\_ref\,1}} \Rightarrow v_{grid} * \cos\left(h\omega_{REF} t + h\theta_{REF}\right) \\ v_{y_{hth}} &= v_{grid} * \mathrm{v}_{\mathrm{hth\_ref\,2}} \Rightarrow v_{grid} * \sin\left(h\omega_{REF} t + h\theta_{REF}\right) \end{aligned} \tag{2}$$

The relation for two reference signals multiplication with input signal is shown in Eq. (2), references are generated internally in Digital Signal Processor with an arbitrary phase and fixed frequency.



(a) (b)

Fig. 3 (a) Block diagram Digital Lock-In Amplifier (b) Frequency Shifting property

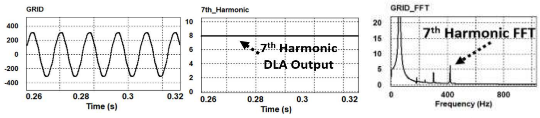
$$v'_{x\_hth} = \frac{v_{nh}}{2}\left[\cos\left((h\omega_{REF} - h\omega_g)t + (h\theta_{REF} - h\theta_g)\right)\right] \tag{3}$$

$$v'_{y\_hth} = \frac{v_{nh}}{2}\left[\sin\left((h\omega_{REF} - h\omega_g)t + (h\theta_{REF} - h\theta_g)\right)\right] \tag{4}$$

Eq. (3) and (4) shows the output of the DLA which contains the amplitude and phase information of desired harmonic.

$$\sin^2(\theta) + \cos^2(\theta) = 1 \tag{5}$$

By applying the Pythagorean theorem as shown in Eq. (11) we solve the Eq. (11) further to extract the amplitude information of given h_{th} harmonic.



(a) (b) (c)

Fig. 4 (a) Harmonic Grid (b)7th harmonic DLA output (c) Grid voltage FFT

$$A_{hth} = \sqrt{\left(\frac{v_{nh}}{2}\right)^2 \begin{Bmatrix} \left[\cos\left((h\omega_{REF} - h\omega_g)t + (h\theta_{REF} - h\theta_g)\right)\right]^2 \\ + \left[\sin\left((h\omega_{PLL} - h\omega_g)t + (h\theta_{PLL} - h\theta_g)\right)\right]^2 \end{Bmatrix}} \tag{6}$$

After further simplification of Eq. (12), following is obtained.

$$A_{hth} = \left(\frac{v_{nh}}{2}\right) \tag{7}$$

Eq. 7 shows the final amplitude of n^{th} harmonic extracted by the DLA. Fig. 4(a) shows the PSIM simulation where harmonics are added at PCC, (b) shows the harmonic amplitude extracted by DLA moreover, the amplitude of extracted harmonic through DLA can be verified through (c) FFT of the PCC voltage.

2.2 Proposed Islanding Detection Algorithm

2.2.1 Passive Detection

Proposed islanding detection method is hybrid islanding detection method. First part of the proposed algorithm is passive algorithm in which grid ambient harmonics are monitored i.e. 5^{th} and 7^{th} harmonics in real time. In case of grid disconnection, the harmonics present at PCC undergoes overshoot or undershoot due to impedance change caused by grid disconnection. Therefore, in order to suspect potential island formation, the overshoot or undershoot in harmonics is measured rather than comparing the harmonics values with fixed threshold values.

Fig. 5 shows the sequence of the proposed islanding detection method. It can be seen that in passive part of the algorithm, 5^{th} and 7^{th} harmonics are monitored in real time, moreover, real time current samples of the 5^{th} and 7^{th} harmonic are compared to 3-line cycles delayed values of the 5^{th} and 7^{th} harmonic. If the current harmonic sample experience the overshoot/undershoot greater than or less than 120% or 80% as compared to 3-line cycle delayed value. These thresholds are optimized after the several hundred tests performed in different time of the day.

$$\left.\begin{aligned} v_{nth}(n) &< 0.8 v_{nth}[n-3] \\ \mathrm{v}_{nth}(n) &> 1.2 v_{nth}[n-3] \end{aligned}\right\rangle ThreeLineCylceDelayed \tag{8}$$

Eq. (8) shows the condition for potential island formation, condition defined above is applicable for both 5^{th} and 7^{th} harmonic both. If any of them of undergoes this change, active detection is turned on in order to verify the islanding condition. Next subsection will explain the active perturbation injection.

2.2.2 Active Method

In order to verify the potential island formation, proposed method incorporates active harmonic injection as depicted in Fig. 5. Active algorithm in proposed hybrid technique is simple, noninvasive active anti-islanding method suitable for grid-connected inverter systems. Once Islanding is suspected by passive method the inverter of the DG injects the output current with a 10th harmonic component into the grid only for three cycles. The harmonic distortion factor (HDF) of the injected tenth harmonic is kept less 3%. Tenth harmonic is selected for active detection in proposed method because 10th harmonic is a non-characteristics harmonic which is not present in the grid.

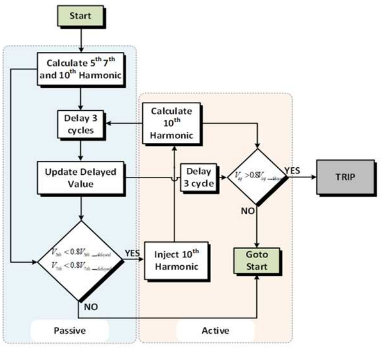


Fig. 5 Proposed DLA based Hybrid Anti-Islanding Technique

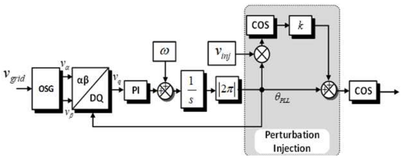


Fig. 6 Conventional DQ-PLL with perturbation injection for active

Therefore, making it easily detectable and distinguishable from other harmonics. The method relies on adding the perturbation in the phase angle of PLL, which is derived from a PLL structure using a second-order generalized integrator (SOGI) based orthogonal signal generator (OSG) PLL. Fig. 6 shows the block diagram of perturbation injection in the 10th harmonic in the phase angle of PLL. In order to prevent continued deterioration of power quality of grid connected inverter, tenth harmonic perturbation is injected only for 3 cycles and monitored through DLA. Eq. (8) shows the condition for the trip signal generation. If the magnitude of the real time magnitude of the tenth harmonic surpass the 20% overshoot, then trip signal is generated, and inverter stops injecting power into the grid.

$$v_{10th}(n) > \overbrace{1.2v_{10th}[n-3]}^{Three-Line\ Cycle\ Delayed} \tag{8}$$

3. Simulation and Experimental Results

PSIM simulations and experiments are carried out with 5kW grid connected inverter to evaluate the performance of the proposed islanding detection method under the different load conditions. The harmonics are first measured from the real grid by a spectrum analyzer and used in the simulation. The real grid measured voltage harmonics are (2nd=150mV), (3rd=2.6V), (5th =4.5V) and (7th = 8.3V). Although harmonics are not affected by the local loads connected to grid connected inverter, however proposed method is tested under 33%, 66% and 100% load conditions as rated power of inverter under test. Fig. 7 shows the simulation of the proposed islanding detection method, inverter is working in grid connected mode from 0s to 0.2s, and grid is disconnected at 0.2s. Island is successfully detected, and trip signal is generated.

Fig. 8 shows the experiment waveform of islanding detection. During the normal grid operation, V_{PCC} is same as the V_{GRID}, however, as shown in figure, as grid is disconnected, voltage at PCC becomes pure sinusoidal due to impedance changes. Therefore, harmonics at PCC also undergoes a decrease, hence after 4-line cycles active algorithm is activated, and inverter starts injecting the 10th order harmonic to verify the potential islanding formation. In order to test the accuracy of proposed islanding detection method, Total of 100 tests were carried out over the period of three weeks at different time of the day. TABLE I shows the comparison table of the proposed method to islanding detection method found in the latest literature. table clearly shows the accuracy of the proposed method is higher than conventional methods, however, robustness, reliability and accuracy is achieved on the cost of higher detection time. Only Reference [6] shows the 100% accuracy as compared to proposed method however, it has higher learning time and also computational burden is also high because high end artificial intelligence technique is employed.

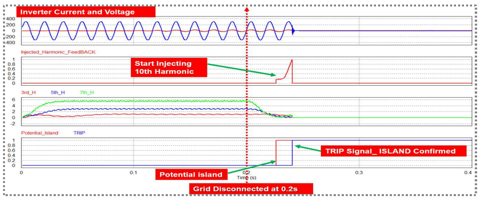


Fig. 7 Proposed Islanding Detection method PSIM Simulation

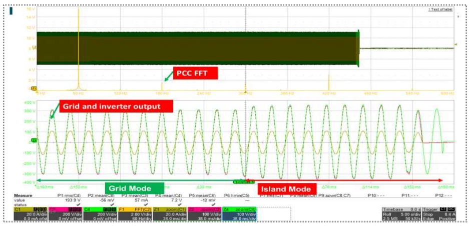


Fig. 8 Proposed Islanding Detection method experiment Results

TABLE I

COMPARISON OF PROPOSED METHOD WITH OTHER TECHNIQUES

Reference	Detection Time	Algorithm	Accuracy %
[3]	0.125s	CART	94.45
[4]	23.9ms	DT	98
[5]	150ms	ESPRIT	95.6
[6]	230ms	PNN	100
Proposed	140ms	DLA	100

4. Conclusion

In this paper a simple, low-cost, accurate and effective hybrid method to detect an islanding situation for grid connected applications has been presented. No additional hardware is required. The proposed have no NDZ unlike conventional passive methods, moreover it does not deteriorate the power quality. Computational burden is also low for whole algorithm i.e. 30uS. Proposed method has been validated by conducting over 100 tests conducted under different load conditions and time of the day.

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