An Anti-Islanding for Multiple Photovoltaic Inverters using Harmonic Current Injections

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ABSTRACT

Islanding phenomenon is one of the major concerns in the distributed generator (DG) systems. Islanding occurs when one or more DGs supplied local loads without connecting to the grid utility. This unintentional condition must be detected with the minimum time possible to prevent the hazardous effects to a person worked in the system or equipment connected to the network. The two main methods of anti-islanding are passive and active methods. The passive methods are excellent in the speed of detection and power quality. However, the passive have relatively large non-detection zone (NDZ). On the other hands, the active methods have less relatively small NDZ and still provide a good speed of detection. This paper proposes an anti-islanding technique for multiple grid-connected inverters in photovoltaic (PV) system based on an active method by injecting harmonic currents with the same or different harmonic orders (h), 5^{th} and 9^{th} harmonics. Due to its excellent algorithm looking at specific frequencies, the Goertzel algorithm is employed in this paper to identify frequency components. This algorithm extracts specific voltage component monitoring the change at the point of common coupling (PCC), as a result the islanding condition can be diagnosed by considering the change in impedance related to injecting harmonics during connecting and islanding condition. Simulation results using PSIM software confirm the effectiveness to the technique in accordance with the requirements of the interconnection standards, IEEE Std. 1547 and IEEE Std. 929-2000.

Keywords: Islanding, Distributed Generator, Multiple Inverters, Harmonic Current

1. INTRODUCTION

Nowadays, the renewable energy industry is one that is rapidly growing in many countries. New renewable energy includes wind power, micro-hydro, photovoltaic (PV), and landfill gas. They have become alternative energy source to supply demanded energy consumption. In Thailand, solar power has become popular due to its tropical climate. PV grid connected generation systems have been installed in many areas with the potential of solar power. In distributed power generation system, requirements are highly reliable and safety operation with high power quality generation. One of the main problems in DG system is called islanding which occurs when generator is disconnected from the utility while still supply local loads. Islanding occurs because of various reasons and can be divided into two main groups, unintentional and intentional situations. Unintentional islanding situations range from accidental opening of the electrical supply while the protection system fails to detect, sudden change in the network system, to human error and natural phenomena. Intentional situations are mostly related to the system and/or device maintenance and system modification [1]. A failure to detect islanding condition or system without anti-islanding is harmful to human including devices installed. For these reasons, IEEE Std. 929-2000 [2] and IEEE Std. 1547 [3] have become specified mandatory standard regulations.

The method of islanding detection can be divided into two categories [4]-[5].

1. Passive methods - The passive methods detect abnormalities related to the islanding conditions. The implementation of these methods is based on the monitoring of the change in variables of utility grid by sensors. Passive methods have a large non-detection zone (NDZ).

2. Active methods - The active methods introduce the disturbance to the DG system and analyse signals at particular points for the islanding detection. These methods can degrade the power quality due to disturbance signal and must be concerned. Active methods have small non-detection zone (NDZ) compared with those of passive methods.

Table 1 summarizes comparison of approximate detection times obtained from different conventional methods for single inverter anti-islanding which have been proposed in the literature.

The impedance monitoring is one of the most popular active methods. The harmonic current is injected by the inverter and the change in voltage at

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Table 1: *Comparison of Detection Time of Different Conventional methods.*

Detection method	Detection time (s)
Over/Under Voltage (OUV)	**0.03 / 0.05 [6]**
Over/Under frequency (OUV)	**0.02 / 0.02 [6]**
Active Frequency Drift with Positive Feedback (AFDPF)	**0.09 [7]**
Current injection	**0.02 [8]**

PCC which depends on the impedance connected to PCC is then observed for anti-islanding. Since the detection time is critical, many researchers have proposed different approaches in order to find the fast calculation algorithm for islanding condition detection. Many of them applied their methods to single inverter while in the practical DG system it would be more than one single inverter installed i.e. a PV farm with two or more PV inverters running in parallel on the same utility grid. Previous works have been proposed for multiple inverter applications such as both inverters based on OUV/OUF method. They still have NDZ like in a single inverter, and both inverters based on Active/Reactive Power Variations connecting do not work perfectly or both inverters based on AFDPF work well for multiple inverters [9], but the speed of anti-islanding detection is slower than conventional current injection method [10]. On the other hand, harmonic current injection has trade off with a power quality because more multiple inverters connected will increase the harmonic polluted to the utility grid. However, this method is faster than AFDPF method and successful detected with no NDZ when it was applied for a suitable case.

The main aim of this paper is to propose the islanding detection technique applied to multiple PV inverters connected in DG system. The harmonic components are injected to the inverter output and the Goertzel algorithm is applied for spectrum analysis at the point of common coupling. However, the multiple inverters connected or grid polluted can cause an anti-islanding detection failure. Thus, this must be analysed and suggested how to fix unsuccessful case. As a result, the island condition can be accurately detected with a very short time.

2. ISLANDING DETECTION SCHEME

For a solar DG system, PV inverter is connected to the utility grid at the PCC as shown in Fig. 1. In the normal grid connecting operation, the impedance at the PCC, Z_{PCC}, can be determined from a parallel configuration of Z_{load} and Z_{grid} . Then, the harmonic voltage component at the PCC ($V_{PCC(h)}$) after injected the harmonic current of order h is derived as given in (1).

$$V_{PCC(h)|Connecting} = \left(\frac{Z_{load}Z_{grid}}{Z_{load} \times Z_{grid}}\right) I_{inv(h)} \qquad (1)$$

Where: $I_{inv(h)}$ is harmonic current component of order h of inverter current. In islanding condition, the system on DG side is disconnected from utility grid. In this case, Z_{PCC} is equal to Z_{load}. Similarly, the harmonic voltage component at the PCC at the islanding condition is as follow:

$$V_{PCC(h)|Islanding} = Z_{load} I_{inv(h)} \qquad (2)$$

The propose method measures the $V_{PCC(h)}$ before sending to a digital signal processing approach for an analysis in frequency domain. The PV inverter injects harmonic currents of specific harmonic orders i.e. 3^{rd}, 5^{th}, 7^{th}, and 9^{th}. The harmonic orders and magnitude of harmonic currents are considered from the percentage of maximum harmonic current recommended in IEEE Std. 1547 (see Table 2) [3]. However, in the case that the grid-connected voltage already contains large individual harmonics generated by multiple inverters themselves or polluted by disturbing nonlinear loads, other odd harmonic orders can be alternative choices for detection. Otherwise the harmonics will be summed and may exceed the IEEE standard [6].

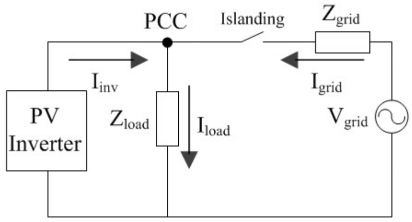

Fig.1: *The PCC impedance network of a single inverter connected to grid.*

Table 2: *Percent of Maximum Harmonic Current Distortion [3].*

Odd harmonics (order h)	Percent (%)
$h < 11$	**4.0**
$11 \leq h < 17$	**02.0**
$17 \leq h < 23$	**1.5**
$23 \leq h < 35$	**0.6**
$35 \leq h$	**0.3**

3. PARALLEL OPERATION

The PV farm is the example case that two or more inverters have been installed in parallel in the same feeder connected to the utility grid [7]. Therefore, the islanding detection system should be installed to avoid the damage in the system, similar to the system with a single inverter [2]. The structure of parallel operation of PV inverters is showed in Fig. 2.

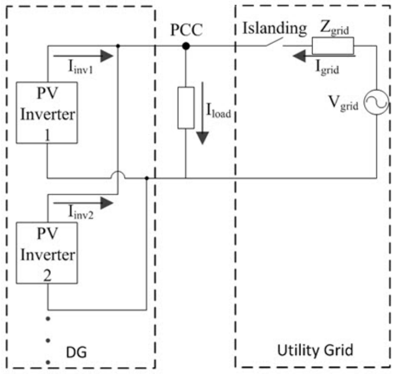

Fig.2: *The PCC impedance network of multiple inverters.*

4. GOERTZEL ALGORITHM

Goertzel algorithm is a technique to compute frequency components of the signal. Unlike general Discrete Fourier Transform (DFT) and according to its algorithm considering at pre-selected frequencies, a short computation time can be obtained [8, 11-13]. It can be used to perform harmonic detection for reference generation for active filtering which requires a minimum computation time [8]. Therefore, it is suitable to classify the harmonic components when islanding occurs. For a single frequency, this algorithm is considerably faster than Fast Fourier Transform (FFT) since DFT calculates many complex values for obtaining amplitude and phase of interested frequency. On the other hand, Goertzel algorithm calculates directly amplitude and phase of frequency of interest based on the N-point DFT as in (3).

$$X[k] = \sum_{n=0}^{N-1} x[n] \cdot e^{-j((2\pi)/N)\cdot n\cdot k} \quad (3)$$

$$\frac{k}{N} = \frac{f_{int}}{f_s} \quad (4)$$

The bin width equation refers to the frequency resolution of the N-point DFT is given (5).

$$\text{bin width} = \frac{f_s}{N} \quad (5)$$

The transfer function of the Goertzel algorithm in z-domain is:

$$H(z) = \frac{1 - e^{-j((2\pi k)/N)} z^{-1}}{1 - 2\cos((2\pi k)/N) z^{-1} + z^{-2}} \quad (6)$$

Hence, the per-sample equation is given in (7).

$$v[n] = x[n] - cos\left(\frac{2\pi k}{N}\right) v[n-1] - v[n-2] \quad (7)$$

Where:

$x[n]$ = current input signal sample ($n = 0, 1, \ldots, N-1$)
k = index for a discrete frequency bin ($k = 0, 1, \ldots, N-1$)
N = number of input signal samples
f_{int} = the frequency of interest
f_s = the sampling frequency
$v[n]$ = intermediate value
$v[n-1]$ = intermediate value of the previous sampling
$v[n-2]$ = intermediate value of twice previous sampling

The Goertzel algorithm runs the per-sample equations N times. After running the per-sample equations N times, the algorithm calculates the results for magnitude and phase of interested frequency. However, islanding detection refers only magnitude component, the magnitude which exceeds the set value will determine the present of islanding phenomenon. By contrast, if the magnitude is less than the set value, algorithm will be reset the intermediate values and then re-computing the per-sample equation. The magnitude component ($y[N]$) equation is derived as in (8).

$$y[[N]]^2 = v^2[N-1] + v^2[N-2] - v[N-1]v[N-2]2\cos\left(\frac{2\pi k}{N}\right) \quad (8)$$

5. RESULTS

To verify the proposed technique, the system illustrated in Fig.2 was simulated using PSIM simulator [9]. The circuit diagram of multiple inverters is shown in Fig. 3.

System parameters used in simulations are described in Table 3. The magnitudes of the injected harmonic currents are controlled at 2% of fundamental current, less than 4% according to the standard (see Table 2). The first simulation test is taken with two inverters connected in parallel to the utility grid inject the harmonic currents with different order, the 5^{th} and 9^{th}. For the 5^{th} harmonic current injection, the appropriate parameter set of Goertzel algorithm is obtained by the following procedures. Firstly, the switching frequency of 20 kHz is selected. Then, other parameters can be calculated by using (3)-(5), f_s = 20 kHz, f_{int} = 250 Hz and the N-point= 400. Similarly, f_s, f_{int} and the N-point are set to 20 kHz, 450 Hz and 400 respectively for the 9^{th} harmonic case. As a result, the resolutions of the Goertzel algorithm for both cases are 5 Hz and 9 Hz respectively. The simulation is set that the grid is disconnected at the t = 0.8 s which indicates the islanding phenomenon. Fig. 4 shows the related voltage and current waveforms

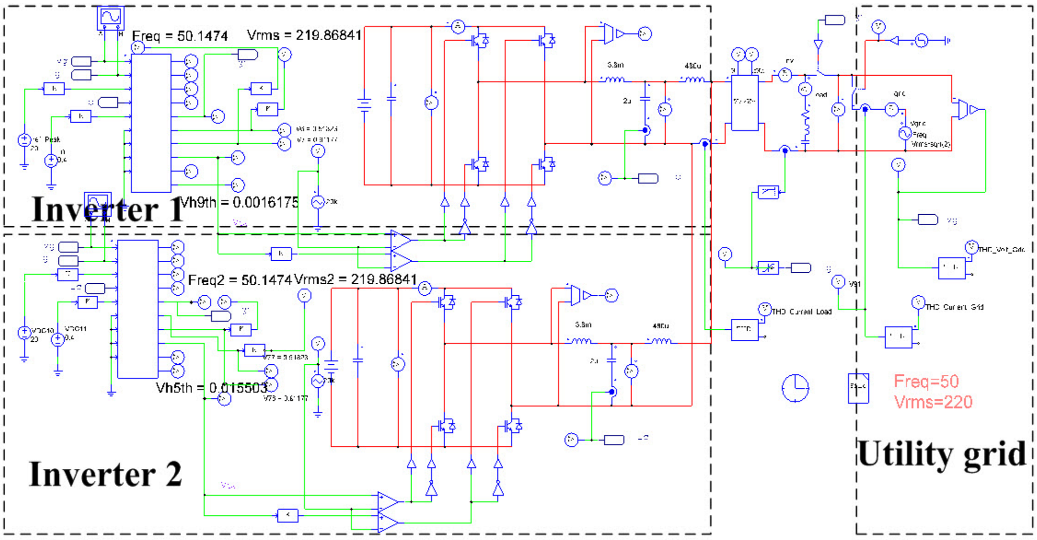

Fig.3: *The simulation circuit of multiple grid connected inverters.*

when the islanding condition occurs. The $V_{PCC(5^{th})}$ and $V_{PCC(9^{th})}$ are monitored for islanding detection. It should be noted that the technique can detect the islanding and disconnected the system approximately within one cycle of fundamental frequency or 0.02 second. The spectrum of V_{PCC} and zoom area of voltage components during the grid-connected operation is shown in Fig. 5. Fig. 6 shows the spectra of VPCC after the islanding occurs. It is clearly seen from Fig. 6 that magnitude of $V_{PCC(5^{th})}$and $V_{PCC(9^{th})}$ are significantly higher than that of a normal grid-connected operation due to the change of impedance at the PCC.

Table 3: *System Parameters.*

Parameter	Values	Unit
Rated output power	3.11	kW
Input Voltage	380	V
Output Voltage	220	V
Output Frequency	50	Hz
DC-Link capacitor	1000	μF
Inverter switching frequency	20	kHz
Inductor L_1 of LCL filter	3.8	mH
Capacitor C of LCL filter	2	μF
Inductor L_2 of LCL filter	480	μH

The second test is carried out under the condition that both inverters inject 9^{th} harmonic currents. The parameters used in Goertzel algorithm are the same as in the first test. The islanding again, occurs at t=0.8 s. The waveforms of anti-islanding operation are shown in Fig. 7 showing the anti-islanding operation within one period of fundamental period. The magnitude of $V_{PCC(9^{th})}1$ and $V_{PCC(9^{th})}2$ which obtained from an algorithm are the same. The voltage component of $V_{PCC(9^{th})}$ as shown in Fig. 8 in-

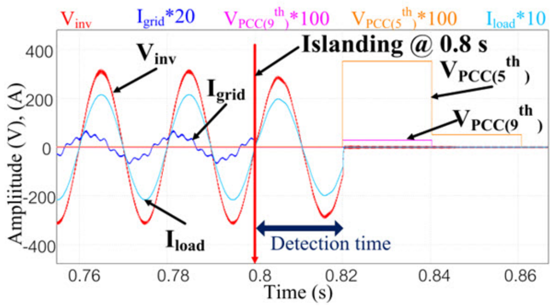

Fig.4: *The anti-islanding waveforms of two parallel inverters with 5^{th} and 9^{th} harmonic current injection.*

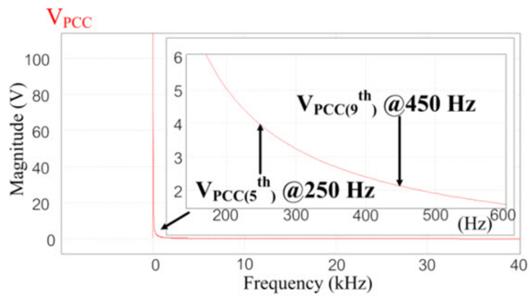

Fig.5: *The V_{PCC} spectra during the grid connected condition with 5^{th} and 9^{th} harmonic current injections.*

creased considerably during islanding mode as shown in Fig. 9.The 5^{th} and the 9^{th} current components are extracted from Iload for the calculation of harmonic distortion factor when islanding occurs. The distortion factor of the 5^{th}, 9^{th} from the first test and the 9^{th} from the second test are 2.4%, 1.69%, and 2.15%, respectively. These values are not exceeded the level provided by standards. With the results obtained, the idea of the presented method has been confirmed

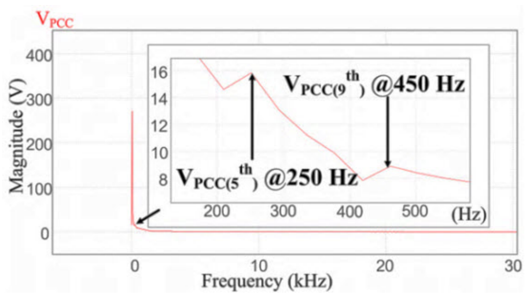

Fig.6: *The V_{PCC} spectra during the islanding mode with 5^{th} and 9^{th} harmonic current injections.*

either with the same or different harmonic orders of the injected currents.

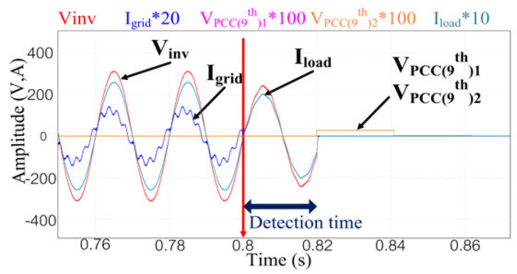

Fig.7: *The anti-islanding waveforms of two parallel inverters with 9^{th} harmonic current injection.*

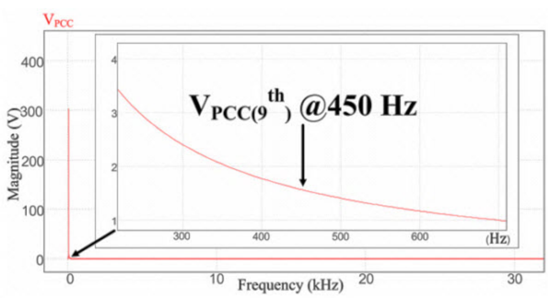

Fig.8: *The V_{PCC} spectra during the grid connected condition with 9^{th} harmonic current injections.*

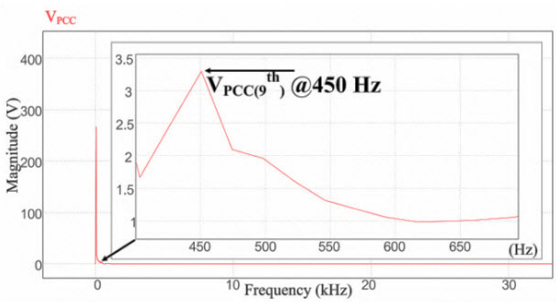

Fig.9: *The V_{PCC} spectra during the islanding mode with 9^{th} harmonic current injections.*

To investigate the harmonic interaction, the third test is carried out under the condition that grid utility contained a specific harmonic of the same order as the injected harmonic (the ninth harmonic in this case).The parameters used in Goertzel algorithm are the same as in the previous test. Fig. 10 shows the waveforms when the method fails to detect the islanding scenario according to the high harmonic content in the grid. In this test, the inverters start to synchronize with utility grid at t= 0.18 s. Then, they detect the magnitude of $V_{PCC(9^{th})}$ which exceeds the limit that set for the islanding condition. However, at this time, the utility grid is still connected to PCC before it is disconnected by the real islanding occurred at t=0.8 s. In this case, inverters cannot work perfectly as shown in Fig. 10. However, to obtain the sucessful islanding detection, the harmonic order of current injected by inverters must be changed. Therefore, both inverters are modified to inject 5^{th} harmonic currents. The voltage component of VPCC(9^{th})is now increased from utility grid but is not affected to the inverters operation since they focus only on 5th harmonic content. The V_{PCC} spectra is illustarted in Fig. 11 during the grid connected condition. Fig. 12 shows the spectra of V_{PCC} after the islanding occurs. It can be seen that the voltage component of $V_{PCC(5^{th})}$ is increased, thus the inverter controller can correctly detect the islanding condition.

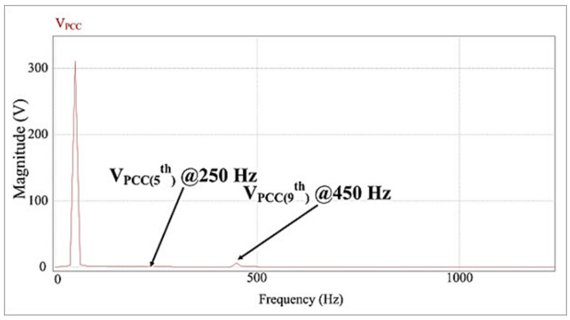

Fig.11: *The V_{PCC} spectra during the grid connected condition with 5^{th} harmonic current injection on the grid polluted with 9^{th} harmonic.*

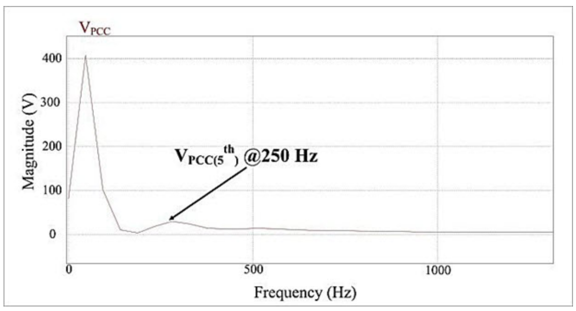

Fig.12: *The V_{PCC} spectra during the islanding mode with 5^{th} harmonic current injection on the grid polluted with 9^{th} harmonic.*

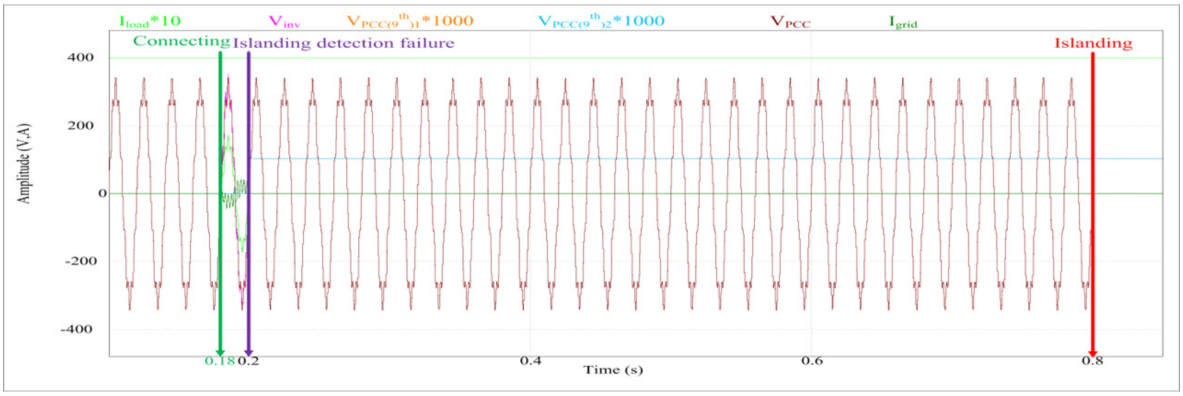

Fig.10: *The waveforms of anti-islanding detection failure with 9^{th} harmonic current injection at t=0.2 s.*

The operation of multiple inverters connected to the grid utility is examined in the last test to confirm its applications. The harmonic components were added to the rated inverter output at the PCC. In this case, the excess power of the local load will feed to the utility grid. Each inverter is controlled with the same algorithm to inject 9^{th} harmonics. Fig.13 shows I_{inv}, inverter output currents obtained when two, three and four rated inverters are connected in parallel. All THD levels are almost the same, approximately 3.11%. This is because each inverter is controlled by the same algorithm and connected in parallel so that the ratio of fundamental and harmonic component will remain almost constant. However, the THD and current distortion will be affected when feeding to local load and utility grid separately. Fig. 14 shows I_{grid}, energized power from PCC when applied the parallel configuration of two, three and four inverters. The THD levels are 5.26%, 4.39% and 4.05% respectively while the 9^{th} harmonic current distortions are 4.92%, 3.90% and 3.54% of fundamental components respectively. From the above results, in this case connecting two parallel inverters is acceptable (produced distortion is below level recommended in the IEEE standard).The results also show that multiple inverters can energize more power to utility grid. However, the number of multiple inverters that can be connected must be determined from the grid power quality and also depended on the amount of harmonic current injection and fundamental current.

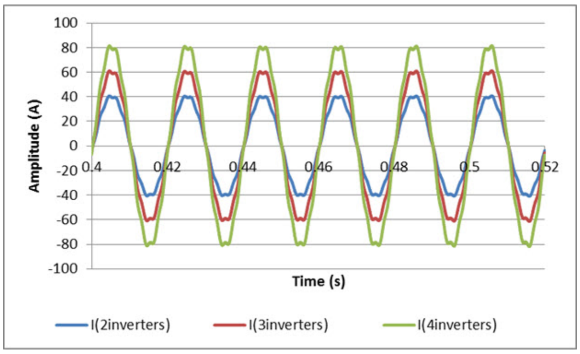

Fig.13: *The output currents of multiple inverters with 9^{th} harmonic current distortion.*

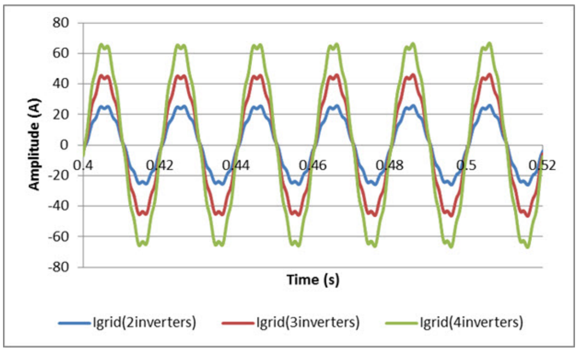

Fig.14: *The grid currents connected with multiple inverters showing 9^{th} harmonic current distortion.*

6. CONCLUSION

In this paper, a current injection method based on the Goertzel algorithm for islanding detection is proposed. Multiple grid-connected inverters inject harmonic currents of the same and different harmonic orders and monitor the change in the magnitude of harmonic components at the point of common coupling and in consequence the islanding condition can be diagnosed. The results confirm the success islanding detection when grid interaction by harmonic and show how to succeed in islanding detection when grid was more polluted by changing harmonic order injection. By using the Goertzel algorithm, the computation time can be reduced significantly and the islanding can be detected within one cycle of fundamental frequency. The simulation results confirm the successful anti-islanding for multiple inverters. In addition, an example of the condition when anti-islanding detection fails is also investigated. With the results obtained, this technique can be developed and applied to a practical DG system.

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