Active Anti-Islanding Method Based on Harmonic Content Detection from Overmodulating Inverters

Vaibhav Sule
The University of Texas at Austin
Baker Hughes, Inc.
Houston, TX
vaibhav.sule7@gmail.com

Alexis Kwasinski
Department of Electrical and Computer Engineering
The University of Texas at Austin
Austin, TX
akwasins@mail.utexas.edu

***Abstract*— This paper proposes a cost effective, simple, and effective method to prevent islanding of grid-connected inverters. It discusses the shortcomings of previous passive and active methods to prevent islanding of utility interactive inverters. A new method, in which the inverter interfacing the main grid and a microgrid is periodically operated in the over–modulation region is proposed. Islanding is detected by measuring the harmonics generated by the over–modulating inverter. It is shown that the proposed method overcomes disadvantages of previously suggested methods without increasing the implementation cost and complexity. Results are validated with the help of simulations and experiments.**

I. INTRODUCTION

THIS paper proposes a new method to prevent islanding of grid connected inverters interfacing an electric grid and a microgrid. Islanding is defined as *"a condition in which a part of the utility system which contains both load and generation is isolated from the rest of the grid, and continues to operate"* [1]. Islanding may occur because of various reasons, such as a fault in the grid which is detected by the utility resulting in the operation of circuit breakers, or intentional disconnection for maintenance [2]. The utility completely loses control over the power interactions in such an island, where the generated power is generated solely by distributed sources. Consequently, power quality levels within the island including a micro–grid and a portion of the grid may not be within the specified limits resulting in damage to consumer equipment. Additionally, energized lines in a supposedly disconnected part of the grid pose safety hazards [3]. The goal of anti–islanding is to disconnect the micro–grid and the grid in order to provide power to the micro–grid load without interactions with the now de–energized grid.

Various methods, passive and active have been proposed to prevent islanding of grid connected inverters [1], [4]–[7]. Passive methods monitor one or more parameters such as voltage and frequency [1]. The inverter is disconnected when the monitored parameters deviate from normal operating values because this condition may indicate an outage in the utility grid. However, if the power delivered to the load by the grid connected inverter(s) is comparable to the power supplied by the utility grid, the measured parameters will only show a small change and the inverter(s) will not be likely disconnected [1], [2]. If the tolerances imposed on the monitored parameters are tightened, then nuisance trips will be observed even when the utility grid is connected. The Non-Detection Zone (NDZ) for an anti–islanding method is defined as, *"the range of local loads (that is, loads within the potential island) for which the islanding prevention method under consideration can be made to fail to detect islanding"* [1]. Active methods aim at reducing this non-detection zone while at the same time preventing nuisance trips [7], [8]. In active methods, a perturbation is continuously imposed on either the current or voltage at the output of the grid connected inverter, and its effect is monitored [1]. When the utility is connected, this perturbation is not noticeable. However, without the grid, the perturbation may be observed leading to a disconnect action for the inverter. Still, in many active methods such as impedance measurement [5], frequency bias [8], harmonic amplitude jump [9] and frequency shift [10], if there is no synchronization or correlation between the various inverters and the imposed perturbations, they may cancel each other out leading to a failure of the system in case of multiple grid–connected inverters [1].

The method proposed in this paper can be classified as an active method for preventing islanding; however, it will be shown that it does not suffer from the disadvantages of the other active methods. Initially, a brief theoretical discussion on Pulse–Width Modulation and existing harmonic

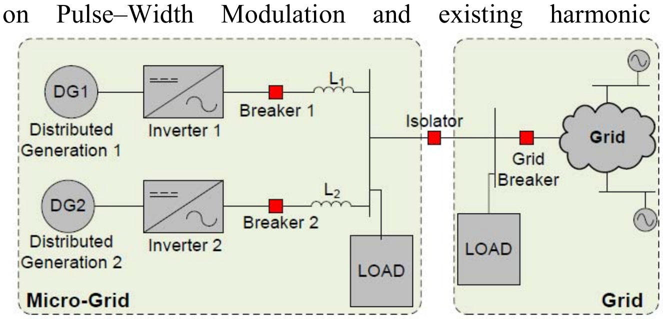

Fig. 1 Distributed System with multiple grid - connected inverters

detection techniques to prevent islanding will be discussed. This will be followed by a description of the proposed method, which will then be validated using simulations performed in PSCAD/EMTDC, and experimental verification.

II. Theoretical Background

A typical arrangement of a micro–grid is shown in Fig. 1, where two distributed sources are interfaced with the load and utility grid with the help of grid–connected inverters. The conductors connecting the inverters to the load are represented by their short line models. Islanding of the micro–grid is said to occur when the grid breaker opens, while breakers 1 and 2 remain closed, with the inverters still functional and delivering power to the load. Anti–islanding methods aim at detecting such situations in order to adopt the necessary strategy required to prevent any instability or safety issues in the system.

A. Pulse Width Modulated Inverters

The modulation index, m_i, for any Pulse Width Modulation (PWM) strategy for a three phase inverter is defined here as [11], [12].

$$m_i = \frac{V_{1,i}}{V_{dc}/2} \tag{1}$$

where, $V_{1,i}$ is the amplitude of the phase voltage fundamental component, of the output voltage of phase i ($i = a,b,c$). V_{dc} is the dc bus voltage at the input of the three phase inverter. For Natural Pulse Width Modulated (NPWM) voltage source inverters, the modulation index is effectively a ratio of the amplitude of a scaled down version of the desired output voltage signal—the modulation signal—and the amplitude of a high frequency saw tooth waveform [11].

When using modulation strategies such as Natural Pulse–Width Modulation (NPWM) or Uniform Pulse–Width Modulation (UPWM), the inverter's fundamental output phase rms voltage increases linearly with the modulation index. However, this is valid only for $m_i \leq 1$. For $m_i > 1$, the output voltage no longer varies linearly as shown in Fig. 2. For $m_i > 1$, the inverter is said to be operating in the over–modulation region.

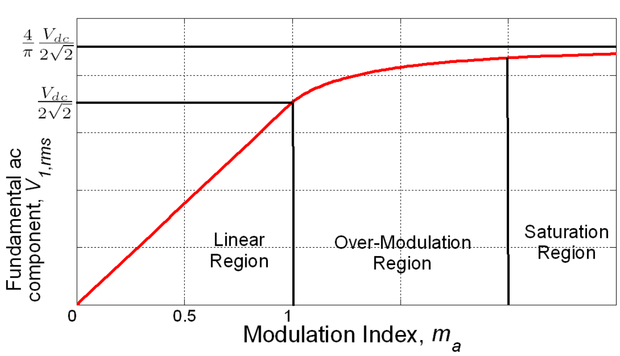

Fig. 2 Modulation regions for a PWM inverter

The output voltage for phase a of the over–modulating inverter can be represented mathematically for one half cycle as in (2).

$$V_a(t) = \begin{cases} \frac{V_{dc}}{2} m_a \cdot \sin(\omega t) & 0 \leq t \leq t_1 \\ \frac{V_{dc}}{2} & t_1 \leq t \leq \pi/\omega - t_1 \\ \frac{V_{dc}}{2} m_a \cdot \sin(\omega t) & \pi/\omega - t_1 \leq t \leq \pi/\omega \end{cases} \tag{2}$$

where, ω is the angular frequency of the modulation signal, and t_1 is the time at which the modulation signal becomes greater than the amplitude of the saw tooth waveform, and can be seen in Fig. 3 which illustrates the output of an over–modulating inverter. For phase a, the value of t_1 can be calculated using

$$t_1 = \frac{\sin^{-1}\left(\frac{1}{m_a}\right)}{\omega} \tag{3}$$

The remaining phase voltages can be easily derived from (2) and (3) by applying the appropriate phase differences.

Theoretically, NPWM does not introduce any harmonics in the baseband when operating in the linear region [12]. However, for all practical implementations, we need to introduce some dead time when switching between the two switches on the same leg of the inverter to avoid accidentally shorting the source (shoot-through). This dead time introduces distortion in the output voltage [13]. The effects of dead time and its compensation have been studied in detail in [13]–[16]. Using any of these compensation techniques, the effect of dead time on the baseband harmonics can be minimized. Uniform PWM on the other hand inherently gives rise to a small amount of odd harmonics in the baseband depending on the switching

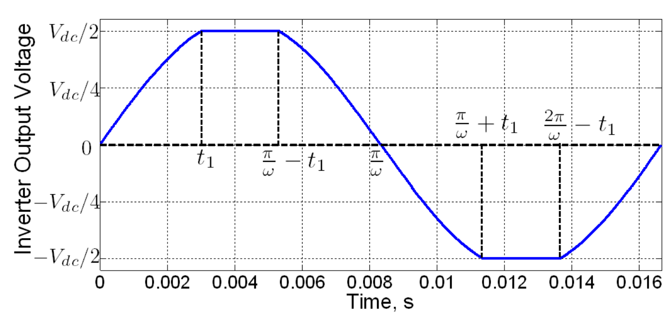

Fig. 3 Filtered output of an inverter operating in the over–modulation region ($m_a = 1.1$)

frequency [12]. However, when the inverter is operated in the over–modulation region, an increase in baseband harmonics is observed for both NPWM and UPWM on account of the appearance of a truncated sinusoid at the output of the inverter as seen in Fig. 3 [17]. With NPWM, the rms amplitude for these harmonic components for $m_a > 1$ is given by

$$V_{n,rms} = \frac{V_{dc}}{\pi}\left[m_a \left(\frac{\sin\left((n-1)\cdot \sin^{-1}\left(\frac{1}{m_a}\right)\right)}{(n-1)} - \frac{\sin\left((n+1)\cdot \sin^{-1}\left(\frac{1}{m_a}\right)\right)}{(n+1)} \right) + \frac{2\cos\left(n\cdot \sin^{-1}\left(\frac{1}{m_a}\right)\right)}{n} \right] \quad (4)$$

where n is the odd harmonic order. A Fourier transform of the waveform in Fig 3 yields the spectrum as shown in Fig. 4. An increase in baseband harmonics is observed in the over–modulation region for any modulation strategy. Triplen harmonic injection methods such as Space Vector Modulation (SVM), which extend the linear range of the inverter, also show an increase in baseband harmonics for $m_a > 1.15$ [12], [17], [18].

B. Harmonic detection method

This method utilizes the fact that inverters inherently generate a small amount of distortion in order to detect islanding of grid–connected inverters [19]. The output voltage total harmonic distortion (THD) for the inverter as defined in

$$THD = \sqrt{\sum_{n=2}^{n=\infty}\left(\frac{V_n}{V_1}\right)^2} \quad (5)$$

is continuously monitored.

When the grid is connected to the load and inverter, a low distortion sinusoidal voltage is imposed on the system. However, during inverter and load islanding, the output of the inverter governs the voltage in the isolated portion of the grid. Also, as most grid–connected inverters utilize a Phase Locked Loop (PLL) for synchronization, the output of the inverter does not become zero, and the inverter "bootstraps", as the PLL synchronizes the inverter's output with itself [20], [21]. As a result, distortion is introduced in the system which if found to be greater than a threshold value, the inverter is taken offline. Although this method can theoretically detect islanding in a wide range of conditions [19], including the case where multiple inverters are connected in the island, it suffers from the problem of selecting a proper threshold for the permissible THD in the system. If a very low value is selected, then even with the grid connected to the load, the THD may exceed the threshold leading to nuisance trips. If a higher value of permissible THD is selected, the method may fail if the total power being supplied by the inverters to the load is comparable to that being supplied by the grid. In short, this method has a large non–detection zone.

Active methods that inject a signal of known frequency other than the grid frequency (generally sub–harmonic) into the system have been devised. However, these methods suffer from various disadvantages as have been studied in [1] and [22]. The main problem with these methods is still selecting a proper threshold level for the THD. Also, in the multiple inverter case, small amount of harmonics being injected by a large number of inverters leads to a considerable reduction in power quality. Another disadvantage of this method is that the injected signal may not have the same phase and frequency for all inverters in the island. Consequently, the inverters may be unable to detect an islanding condition on accord of inadequate distorting signal being observed on the output voltage [1]. An active method that reduces the disadvantages mentioned above is proposed in the following section.

III. Proposed Anti Islanding Method

As shown in Fig. 4, an inverter operated in the over–modulation region introduces odd harmonics, mainly 3rd, 5th and 7th, into the system. In the proposed method, the modulation index, m_i, of the inverters is varied periodically according to (6), in order to inject harmonics into the system.

$$m_i = \begin{cases} m_{op} & 0 \le t \le 9T \\ m_{over} & 9T \le t \le 10T \end{cases} \quad (6)$$

where, m_{op} is the operating modulation index for the inverter during normal operating conditions (grid connected), m_{over} is the modulation index in the over–modulation region, and T is the time period for the grid voltage. This variation of the modulation index is illustrated in Fig. 5. The value for m_{over} is set to 1.1 as it provides a good tradeoff between introducing sufficient harmonics into the system without exceeding the prescribed limit of 5% THD in [23].

As the modulation index of the grid–connected inverter is raised periodically into the over–modulation region, it injects odd harmonics into the system. When the grid is connected, the harmonics introduced into the system voltage

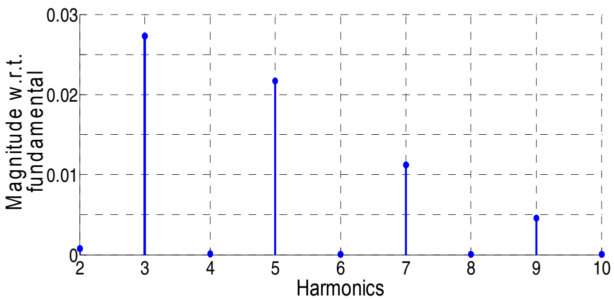

Fig. 4 Harmonic content at inverter output for over–modulated case

are extremely low in magnitude as the grid is stiff. This behavior can be observed in Fig. 5, where the system voltage shows almost no distortion even during periods of over–modulation. However, when the grid is disconnected, the system voltage will exhibit an increased magnitude of odd harmonics (similar to Fig.4), which can be monitored to detect islanding of the system. Instead of measuring the THD of the system, only one or two voltage harmonics are measured (typically the 5^{th} and 7^{th}), as these harmonics are generated primarily by six pulse bridges [18], [24], which will help to reduce the error in detecting islanding.

The advantage of this method is that the threshold value for the permissible voltage harmonics can be set much higher than that which will be encountered typically in a system of this type. This method, unlike the harmonic detection method, does not rely upon a non–linear load, which may or may not be present, to create harmonics in the system [1]. As a result, nuisance trips can be avoided, while at the same time reducing the non–detection zone. Thus, this method aims at reducing the disadvantages encountered by the harmonic detection method which have been discussed earlier. Another advantage of this method is that since the distortion is added to the system for a very short time, even with multiple inverters connected to the system, this method introduces less overall distortion into the grid as compared to other proposed active methods. Additionally, multiple inverters cannot cancel out the perturbations introduced by each other since the perturbations will have the same phase and frequency as the inverters are synchronized with each other by the PLL's. This is an improvement over existing active methods such as impedance measurement [5], frequency bias [8], harmonic amplitude jump [9] and frequency shift [10] among others [1].

IV. SIMULATIONS AND RESULTS

The proposed scheme was simulated using PSCAD/EMTDC. Two scenarios were considered. Firstly, a purely resistive load, and secondly, an inductive load with power factor of 0.89. In both cases, two independently controlled inverters supply power to the load, where, the active power delivered by the inverters is almost equal to the active power delivered by the grid. It has been shown in

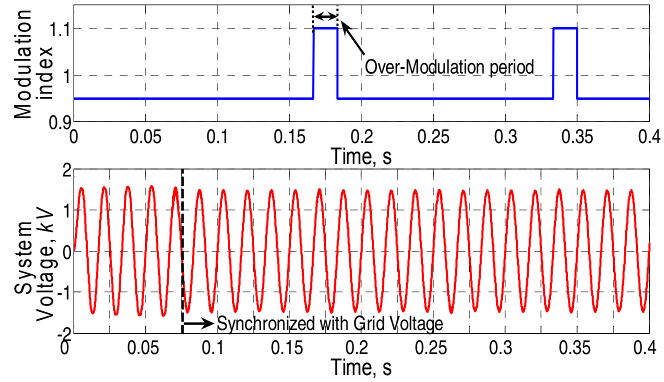

Fig. 5 Variation of modulation index in proposed anti - islanding scheme (above), and corresponding output voltage of inverter (phase a, assuming balanced three phase system) with grid online (below)

[1] that this is a typically difficult system to island. In both scenarios, the nominal line to line system voltage is 1.8kV, rms. Both the inverters are identical in all respects. However, there is no co-ordination or communication between the two inverters. Inverters are connected to the load and grid through circuit breakers, which open whenever islanding is detected. The setup is similar to the one shown in Fig. 1. Instead of using circuit breakers, the inverter itself may be forced to cease operation on detection of islanding. Two cases which seemed to be of importance to the proposed method were studied in both scenarios,. Firstly, the validity of the method was tested wherein there is no overlap in the over–modulation periods of the two inverters. Secondly, to verify if the method would not cause objectionable amount of distortion in the system voltage during normal operation, if multiple inverters are connected, both inverters are over–modulated at the same point of time.

a. Scenario 1: Load = 60 kW

With a purely resistive load, about 20–30 kW is provided by the utility grid. The remaining power (30–40 kW), is delivered by the two inverters. Fig. 6(c) shows the status of the three breakers throughout the simulation.

At around 0.06 seconds, the two inverters synchronize with the grid, and they are connected to the system with the help of breakers 1 and 2. Although there is no synchronization or communication between the two inverters, since similar PLL's are used for synchronization, the two circuit breakers operate simultaneously. At 0.7 seconds, the grid trips, but it can be seen that the inverter breakers are still closed, thus creating an island. Approximately 0.05s after islanding, an over–modulation cycle occurs for inverter 2, which causes the 5^{th} harmonic to exceed the threshold, as shown in Fig. 6(a) and (b). Consequently, islanding is detected, and the controller acts preventing power to be injected back into the main grid.

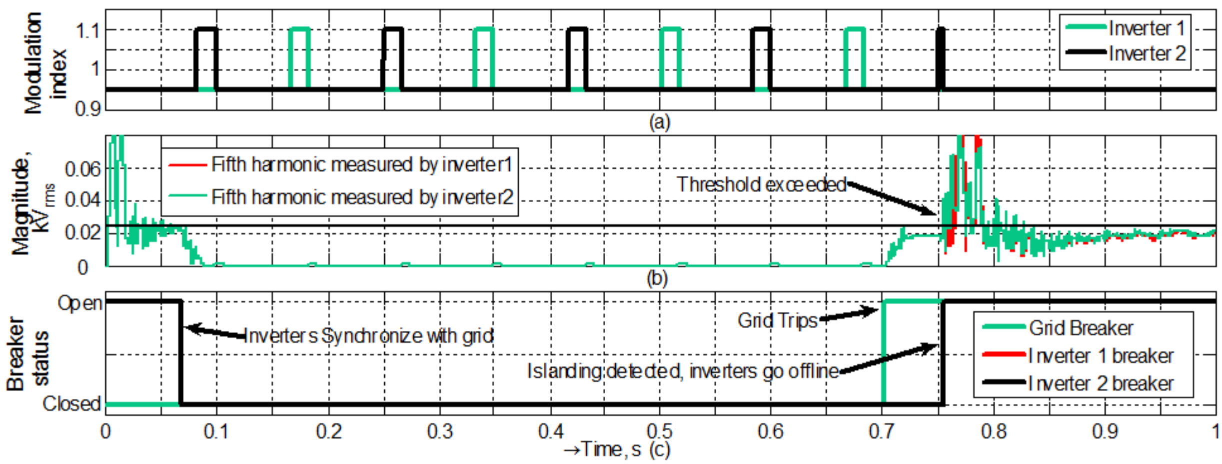

Fig. 6 Results of simulation of proposed scheme for load = 60kW, no overlap in over–modulation period (a) Variation of modulation indices for the two inverters (b) Magnitude of the 5th harmonic as measured by the two inverters (c) Status of breakers

From Fig. 6(b), it can be observed that after synchronization, the contribution of the two inverters to the 5th harmonic in the system is extremely small, even during periods of over–modulation. After islanding occurs at 0.7 seconds, the 5th harmonic in the system becomes noticeable (about 0.015 kV_{rms}). However, this constitutes only about 1.5% distortion, which can be observed even in a healthy system. Thus, it is difficult for the inverters to sense this islanding situation without setting the threshold limit to a very low value, which can and will cause nuisance trips. At time 0.75 seconds, inverter 2 over–modulates, and the magnitude of the 5th harmonic rises sharply. As soon as this value goes above $0.025kV_{rms}$, the two inverters sense that an islanding situation has occurred and disconnect the inverters from the load as can be seen in Fig. 6(b). It can be noted that even if the magnitude of the 5th harmonic in the system voltage, with the grid connected, is larger than 0.025 kV_{rms} on account of other sources of distortion, the threshold can be increased accordingly. The amount of over–modulation can also be increased to detect islanding easily.

Fig. 7 shows the total harmonic distortion introduced by the inverters because of over–modulation, during normal operation of the grid. During normal operation, the proposed over–modulation method contributes less than 0.1% of the THD observed in the load current.

In order to observe the effect on the THD in the load

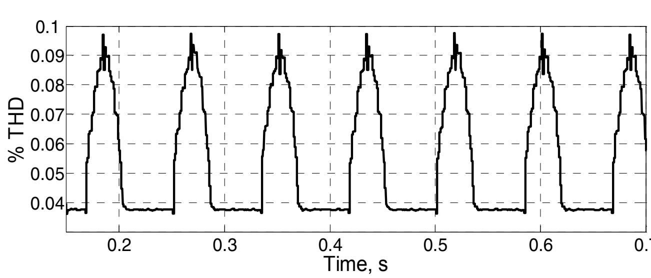

Fig. 7 Total Harmonic Distortion in load current during normal operation

current if the over–modulation periods of the two inverters overlapped with each other, a similar simulation was performed with the modulation indices of the two inverters varied in such a manner that the two over–modulation periods occur at exactly the same time, as shown in Fig. 8(a). The 5th harmonic magnitude, shown in Fig. 8 (b), is similar to the previous case. The breakers' operations can be seen in Fig. 8(c).

In this case, the inverters are taken offline approximately 0.14 seconds after the grid trips. It should however be noted that the maximum time it will take the inverters to detect islanding in this case is 9 cycles of the voltage (≈ 0.15 seconds). Thus, the time seen in the simulation is the worst case scenario wherein the grid trips just when one over–modulation period is complete. An advantage of this method is that this maximum time to detection can be varied by varying the interval between over–modulation periods, depending on the number of inverters in the micro–grid. The THD caused by the two inverters in the load current during normal operation can be seen in Fig. 9.

Fig. 9 demonstrates that during normal operation, the maximum distortion introduced by the two inverters, even with complete overlap in over–modulation periods is still less than 0.17%, which is extremely small. As the two inverters are providing half of the load power, it can be safely assumed that the proposed method will be applicable for the multiple inverter case, without having any adverse effect on the power quality in the grid.

b. Scenario 2: Load = 60 kW, 30 kVAr, lagging

Similar simulations as before were performed for this load. Again, two cases were studied, with and without overlap in the over–modulation periods. The results will be presented without much discussion as they are similar to the previous results. The variations in the modulation indices

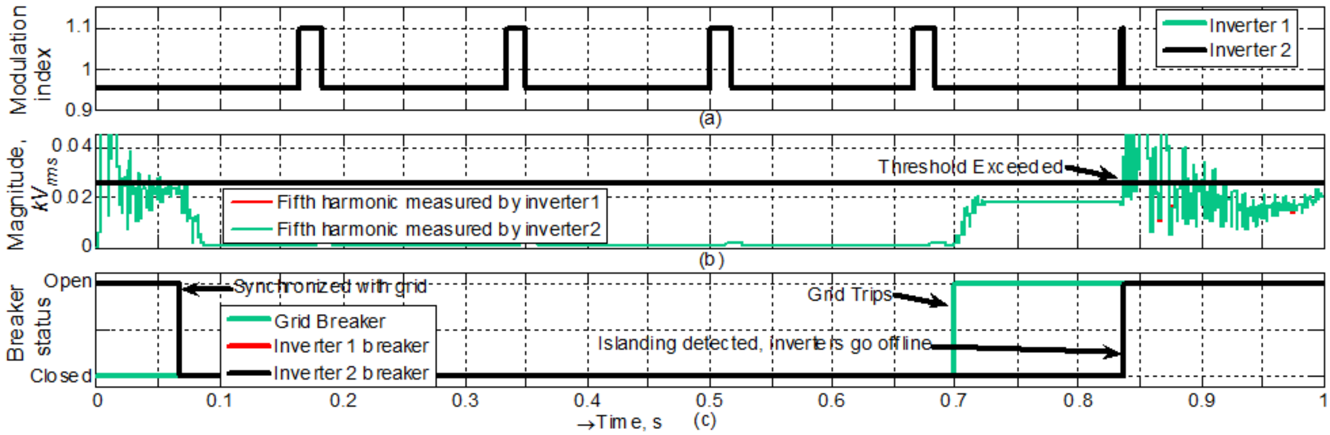

Fig. 8 Results of simulation of proposed scheme for load = 60kW, complete overlap in over–modulation period (a)Complete overlap of over - modulation periods, (b) Magnitude of 5th harmonic as measured by the two inverters, (c) Status of Breakers,

and the measured 5th harmonic voltages are shown in Fig. 10. Again, the THD in the load current is extremely small (<0.07%), as can be seen in Fig. 11.

For the case with complete overlap in the over–modulation periods, only the THD in the load current is shown below (Fig. 12) as the other results are similar to the case with the purely resistive load. The THD was observed to be lower in this case as compared to the purely resistive load. Some of the practical aspects for implementation of this method are discussed in the next section.

From the simulations, the proposed method satisfies the requirements put forth by [3], [23] and [25], as regards, time to de–energize, distortion introduced into grid, voltage regulation, and distortion introduced by each harmonic.

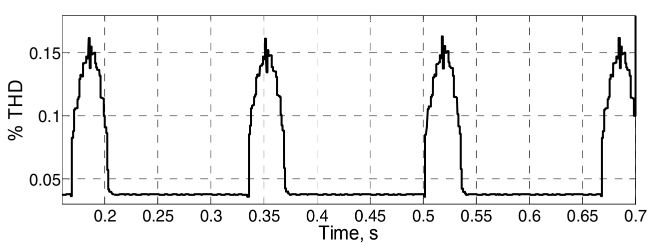

Fig. 9 THD in load current with complete overlap in over - modulation, during normal operation, load = 30kW

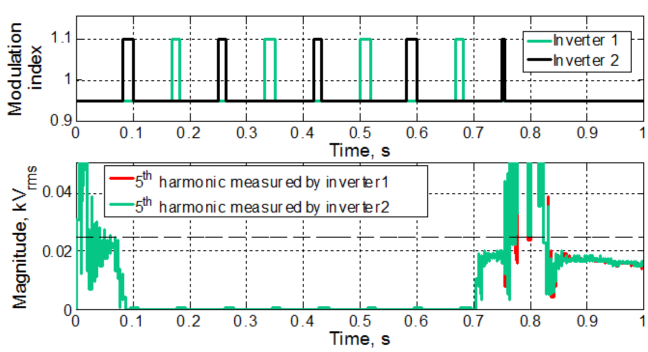

Fig. 10 Modulation indices for the two inverters (above), Magnitude of the 5th harmonic as measured by each inverter (below), inductive load

V. EXPERIMENTAL VERIFICATION

The proposed scheme was verified experimentally using one inverter and a scaled-down version of the grid. In order to simulate a weak grid, a variable-turns autotransformer with a low power rating was connected between the actual utility grid and the load. This effectively weakens the grid significantly as seen by the inverters and the local load. The grid available for testing had a THD of 3.1% without being connected to the inverter. The load used was a 10 Ω power resistor. The modulation index can be varied using the circuit shown in Fig. 13. This circuit basically applies a variable gain to a voltage controlled amplifier. The gain is varied such that the modulation signal forces the inverter to operate in the linear region for about 9 cycles in every 10 cycles. For about 1 cycle, the output of the voltage controlled amplifier becomes larger in magnitude than the triangle wave used for NPWM in the inverter. Consequently, this causes the inverter to operate in the

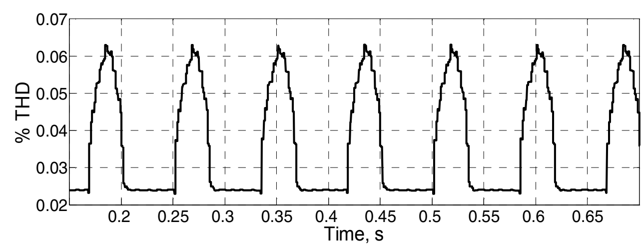

Fig. 11 THD in load current, load = (60 + j30) kVA, no overlap in over - modulation periods

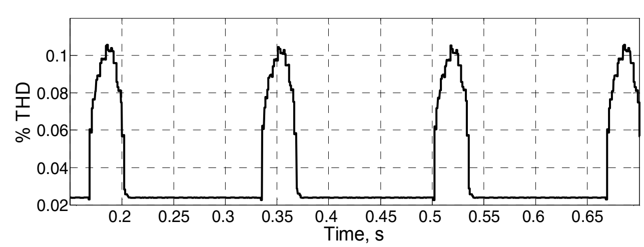

Fig. 12 THD in load current, load (60 + j30) kVA, complete overlap in over–modulation periods

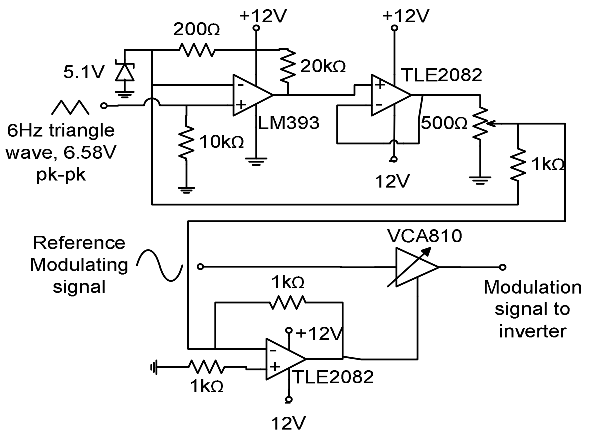

Fig. 13 Control circuit for modulation index control

over–modulation region for approximately one cycle. The gain of the voltage controlled amplifier can be varied to control the amount of over–modulation of the inverter. The modulation signal produced by this control circuit is shown in Fig. 14. The inverter available utilizes a triangle wave with a peak to peak value of 8.0 V for the NPWM. It can be seen from Fig. 14 that the inverter will be driven into over–modulation for about 1 cycle in every 10 cycles.

An eighth order butterworth bandpass filter with a center frequency of 300 Hz was used to measure the fifth harmonic at the output of the inverter. The bandpass filter was an active filter designed using operational amplifiers, and is very cost effective. Fig. 15 shows a block diagram of the connection for the inverter to the grid along with the control and measurement blocks.

Initially, the inverter is synchronized with the grid. Due to the use of the variac, the grid seen by the inverters is extremely weak. The output of the inverter is only about 23 V_{rms} as a larger dc voltage was unavailable. However, since anti–islanding methods are independent of the voltage levels, there is no loss of generality in the experimental verification. With the load connected, the inverter supplies 42 W to the load out of the total 52 W being consumed. This is a situation that may never be seen in practice; however, it forms a worst case scenario for testing the proposed scheme.

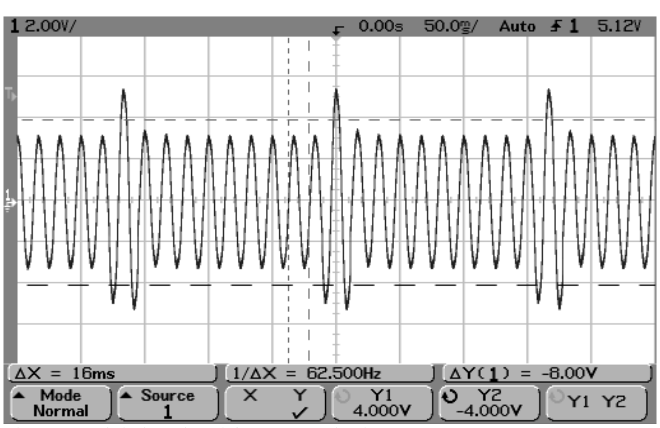

Fig. 14 Modulation signal for proposed scheme

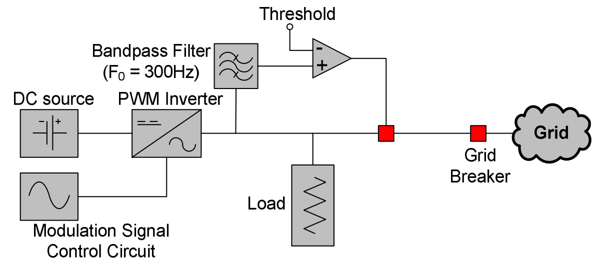

Fig. 15 Block diagram for practical implementation of proposed anti–islanding scheme

A significant difference in the measured fifth harmonic with and without the grid connected will validate the proposed scheme.

Fig. 16 shows the voltage measured at the output of the inverter with the grid connected. The output of the bandpass filter shows the amplitude of the fifth harmonic. The maximum value for the fifth harmonic is found to be about 594 mV. It can be seen that the over–modulation of the inverter causes some distortion of the grid voltage. However, it must be noted that in this case, the grid is weaker than the inverter, a condition that will not occur practically. Even so, the total harmonic distortion in the grid voltage was found to be 3.9%, which is within permissible distortion limits according to [3] and [23].

Fig. 17 shows the output of the inverter with the grid disconnected, along with the output of the filter. With the grid disconnected, the fifth harmonic content in the output of the inverter, when operating in the linear region is found to be less than that found in the grid itself. Also, it can be seen that the output voltage does not sag on grid disconnection. Thus, this is a very difficult situation to detect islanding for any harmonic detection technique. However, as soon as the inverter begins to over–modulate, the magnitude of the fifth harmonic increases significantly. The amplitude of the fifth harmonic goes up to 1 V during each over–modulation period. A threshold limit set anywhere between 700 and 900 mV can easily detect this islanding condition at the first instance of over–modulation, without any nuisance trips.

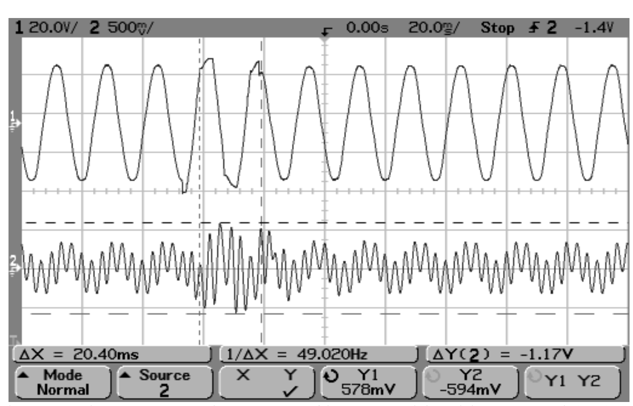

Fig. 16 Voltage measured at output of inverter with grid connected (top), fifth harmonic at output of the bandpass filter

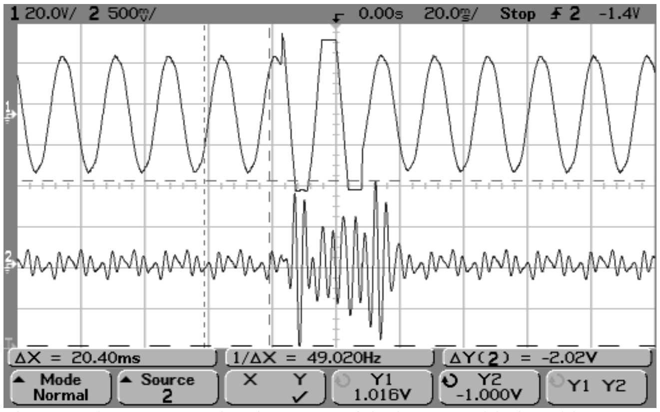

Fig. 17 Voltage measured at the output of the inverter with the grid disconnected (top), fifth harmonic measured by the bandpass filter (bottom)

VI. CONCLUSION

This paper has presented a new active islanding detection method based on periodically operating inverters in a micro–grid in the over–modulation regime. From the simulations and the experimental verification, it can be concluded that the proposed method is capable of detecting islanding effectively. The proposed method seems to have advantages over various passive and active methods proposed in the past. Additionally, it has been shown that the proposed method introduces very low amount of distortion into the load, well within prescribed requirements, even though a majority of the load power is delivered by grid–connected inverters. Another advantage is that the inverters can be configured to detect islanding only during their over–modulation periods which should result in minimized nuisance trips, even if the sensitivity is increased.

VII. REFERENCES

[1] W. Bower and M. Ropp, "Evaluation of islanding detection methods for utility-interactive inverters in photovoltaic systems," Sandia National Laboratories SAND2002-3591, 2002.

[2] R. A. Jones, T. R. Sims, and A. Imece, "Investigation of potential islanding of dispersed photovoltaic systems," Sandia National Laboratories, Albuquerque, New Mexico, Technical Report SAND-87-7024, 1988.

[3] "IEEE Recommended Practice for Utility Interface of Photovoltaic (PV) Systems," IEEE standards coordinating committee 21 on photovoltaics IEEE standards 929-2000, 2000.

[4] S. J. Ranade, N. R. Prasad, S. Omick, and L. F. Kazda, "“A Study of Islanding in Utility-Connected Residential Photovoltaic Systems, Part I: Models and Analytical Methods," *IEEE Transactions on Energy Conversion*, vol. 4, no. 3, pp. 436-445, Sep. 1989.

[5] M. Ropp, M. Begovic, and A. Rohatgi, "Prevention of Islanding in Grid-Connected Photovoltaic Systems," in Progress in Photovoltaics, vol. 7, 1999, pp. 39-59.

[6] A. Wyote, R. Belmans, K. Leuven, and J. Nijs, "Islanding of Grid-Connected Module Inverters," in Proceedings of the 28th *IEEE Photovoltaic Specialists Conference*, 2000, pp. 1683-1686.

[7] M. E. Ropp, M. Begovic, and A. Rohatgi, "Analysis and performance assessment of the active frequency drift method of islanding prevention," *IEEE transactions on Energy Conversion*, vol. 14, no. 3, pp. 810-816, Sep. 1999.

[8] S. Yuyama, et al., "A High-Speed Frequency Shift Method as a Protection for Islanding Phenomena of Utility Interactive PV systems," in *Solar Energy Materials and Solar Cells*, vol. 35, 1994, pp. 477-486.

[9] F. Bertling and S. Soter, "A novel converter integrable impedance measuring method for islanding detection in grids with widespread use of decentral generation," in Power Electronics, Electrical Drives, Automation and Motion, 2006. SPEEDAM 2006. International Symposium on, 2006, pp. 503-507.

[10] G. A. Kern, R. H. Bonn, J. Ginn, and S. Gonzalez, "Results of Sandia National Laboratories Grid-Tied Inverter Testing," in 2nd *World Conference and Exhibition on Photovoltaic Solar Energy Conversion*, Vienna, Austria, 1998.

[11] N. Mohan, T. M. Undeland, and W. P. Robbins, Power electronics: converters, applications, and design, 2nd ed. New York: Wiley Inc., 1995.

[12] A. Kwasinski and P. T. Krein, "An integrated 42-V drive design for automobile loads with a low-distortion overmodulation strategy," *IEEE Transactions on Power Electronics*, vol. 21, no. 3, pp. 648-658, May 2006.

[13] D. Leggate and R. J. Kerkman, "Pulse based dead time compensator for PWM voltage inverters," in Proceedings of the 1995 IEEE *IECON 21st International Conference on Industrial Electronics, Control, and Instrumentation*, vol. 1, 1995, pp. 474-481.

[14] R. Ueda, T. Sonoda, Y. Inoue, and T. Umezu, "Unstable Oscillating Motor in PWM Variable Speed Drive of Induction Mode and its Stabilization," in IEEE *IAS Annual Conference*, 1982, pp. 686-691.

[15] Y. Murai, T. Watanabe, and H. Iwasaki, "Waveform Distortion and Correction Circuit for PWM Inverters with Switching Lag–Times," *IEEE Transaction on Industry Applications*, vol. 23, no. 5, pp. 881-886, Sep. 1987.

[16] S. Jeong and M. Park, "The Analysis and Compensation of Dead–Time Effects in PWM Inverters," *IEEE Transaction on Industrial Electronics*, vol. 38, no. 2, pp. 108-114, Apr. 1991.

[17] A. Kwasinski, P. T. Krein, and P. L. Chapman, "Time Domain Comparison of Pulse–Width Modulation Schemes," *IEEE Power Electronics Letters*, vol. 1, no. 3, pp. 64-68, Sep. 2003.

[18] A. Kwasinski and P. T. Krein, "An integrated approach to PWM through 3–dimensional visualization," in Power Electronics Specialists Conference, 2004. PESC 04. 2004 IEEE 35th Annual , vol. 6, 2004, pp. 4202-4208.

[19] H. Kobayashi, K. Takigawa, and E. Hashimoto, "Method for preventing islanding phenomenon on Utility Grid with a number of small scale PV systems," in Proceedings of the 21st *IEEE Phototvoltaic Specialists Conference*, 1991, pp. 695-700.

[20] R. Best, Phase-Locked Loops: Theory, Design and Applications, 2nd ed. McGraw Hill Inc., 1993.

[21] P. V. Brennan, Phase-Locked Loops: Principles and Practice. MacMillan Press Ltd., 1996.

[22] S. K. Chakravarthy and C. V. Nayar, "Determining the frequency characteristics of power networks using ATP," in *Electric Machines and Power Systems*, 1997, pp. 341-353.

[23] "IEEE recommended practices and requirements for harmonic control in electrical power systems," IEEE Std 519-1992, 1992.

[24] S. Perera, V. J. Gosbell, and B. Sneddon, "A study on the identification of major harmonic sources in power systems," in Australasian Universities Power Engineering Conference, Melbourne, 2002.

[25] "IEEE Standard for Interconnecting Distributed Resources with Electric Power Systems," IEEE Standards 1547-2003, 2003.