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Low Order Harmonic Cancellation in a Grid Connected Multiple Inverter System Via Current Control Parameter Randomization

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***Abstract*—In grid connected multiple inverter systems, it is normal to synchronize the output current of each inverter to the common network voltage. Any current controller deficiencies, which result in low order harmonics, are also synchronized to the common network voltage. As a result the harmonics produced by individual converters show a high degree of correlation and tend to be additive. Each controller can be tuned to achieve a different harmonic profile so that harmonic cancellation can take place in the overall system, thus reducing the net current total harmonic distortion level. However, inter-inverter communication is required. This paper presents experimental results demonstrating an alternative approach, which is to arrange for the tuning within each inverter to be adjusted automatically with a random component. This results in a harmonic output spectrum that varies with time, but is uncorrelated with the harmonic spectrum of any other inverter in the system. The net harmonics from all the inverters undergo a degree of cancellation and the overall system yields a net improvement in power quality.**

***Index Terms*—Low order harmonics, multiple inverter systems, net harmonics.**

I. INTRODUCTION

MULTIPLE string inverters are frequently used to connect a PV system to the network [1]. In this approach, each panel is connected through its own inverter, the inverter units being connected in parallel up to the required volt-ampere rating of the system (Fig. 1). This avoids the need to run long lengths of high current dc cabling, with the attendant problems of expensive circuit breakers. It is normal practice for the output current of each inverter to be controlled to be sinusoidal, with low harmonic levels, and at unity power factor with respect to the network voltage.

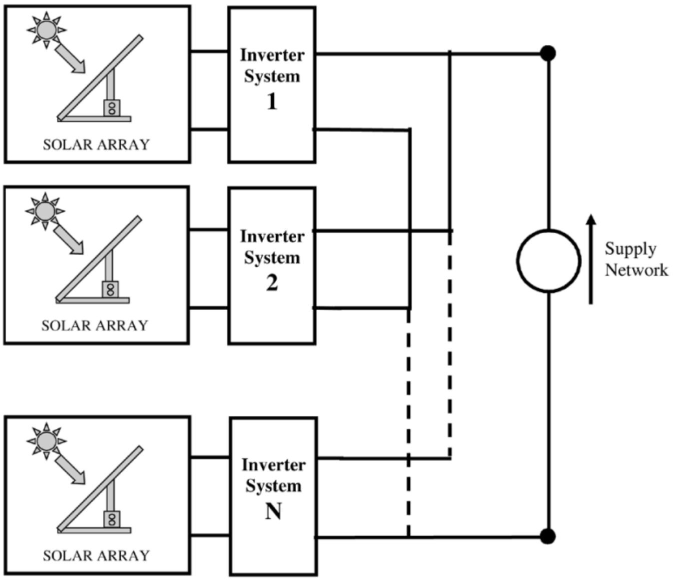

Fig. 1. Grid connected, multiple string inverter system.

Low harmonic levels are desirable since harmonics have long been recognized as causing a number of operational problems to the grid network [2]–[4]. Some of the major effects caused by harmonics include capacitor bank failure, overvoltage and overcurrent on the network, dielectric breakdown of insulated cables and kWh metering errors. To preserve the quality of the utility current and voltage, set limits are imposed on the current and voltage harmonics that may be injected into the grid [5], [6]. However, as more and more distributed generation systems are being interfaced to the network, the problem of harmonic injection into the grid is becoming an increasing problem [7]–[12]. For this reason, there is considerable motivation to improve grid connected inverter performance through the reduction, or ideally complete elimination, of the output harmonics.

Several techniques aimed at inverter system harmonic improvement have been presented. Holmes and McGrath [13] considered the effect of a number of different PWM strategies in various converter topologies. It was demonstrated that certain PWM strategies and sampling techniques could help eliminate particular side-band switching harmonics. This work also identified further opportunities for harmonic elimination in multilevel cascaded inverter systems. Liang *et al.* [14] described the use of Walsh Functions in a single phase full bridge inverter for the purpose of voltage harmonic elimination at the inverter output. The Walsh Function technique allowed the harmonic amplitudes of the inverter output voltage to be expressed as functions of the inverter switching angles. A series of linear algebraic equations could then be solved to eliminate unwanted harmonics. Infield [15] discussed the manner in which random

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phase harmonics in multiple inverter systems combined. In particular, the work was applicable to switching harmonics, which are random in phase. Mathematical rules, based on probabilistic integrals, were formulated to help assess the overall degree of harmonic cancellation arising from multiple connection of inverter systems to a common point.

This paper suggests a new idea to improve the overall current harmonic output of a grid connected multiple inverter system. In particular, the work focuses on reducing low order current harmonics. This is achieved through simple randomization of the inverter current control parameters. This technique is shown to significantly reduce the correlation of low order current harmonics between inverters. As a result, on average, the inverter harmonics at the common point of coupling are likely to demonstrate a degree of cancellation, as opposed to harmonic reinforcement when correlated.

II. GRID CONNECTED INVERTER HARMONICS

The harmonics in the output current of an inverter can be grouped according their source: switching harmonics which are related to the PWM circuits in each inverter and lower frequency harmonics which are due to deficiencies in the control of the inverter output current. The majority of the switching harmonics are easily filtered at the inverter output. The low order harmonics, however, are at frequencies much closer to the fundamental. Therefore, it is more difficult to filter these harmonics without impairing the fundamental current waveform.

The output current harmonics related to the PWM are synchronized to the clock circuits within the inverter controller and therefore, will not be correlated because the crystal controlled clocks within each inverter are usually independent. A recognized power quality benefit of this arrangement is that the harmonic distortion arising in each inverter is uncorrelated and therefore cancellation will take place in multiple inverters systems. The harmonics due to the current controller performance will, however, behave differently. It is normal to produce a current reference waveform within the inverter, which specifies the magnitude and power factor of the output current in accordance with the active and reactive power generation requirements at a particular time. For a grid connected system, the current reference waveform in each inverter must be synchronized to the common network voltage waveform. Therefore, any low order harmonics resulting from controller deficiencies will also be synchronized to the common network voltage and the harmonics produced by individual converters will have a high degree of correlation. This will mean that the lower order harmonics from each inverter will be additive.

The grid-connected inverter has to drive current against the supply voltage and impedance, which are not fixed quantities. Grid connected inverter performance has been shown to be very much dependent on grid operating conditions [16]. Controlling current to be injected into the grid network is, therefore, considerably more difficult than controlling current into fixed loads such as motor windings or isolated consumer load systems. The output current waveform fidelity is dependent on the tuning of the current control loop but changes in the grid supply characteristics mean that it is not possible to achieve an optimally tuned output current loop at all times. Normally the inverter output current is tuned by adjusting settings within the controller while monitoring the low order harmonics. By trial and error, various harmonics can be minimized and total harmonic distortion (THD) can be reduced. A point is normally reached where further tuning does not produce any further improvement in THD. By adjustments to the controller tuning, however, it is possible to alter which harmonics are suppressed while maintaining the total harmonic distortion reasonably constant. This is due to the interaction between the controller dynamics and the dynamics of the supply and line inductance.

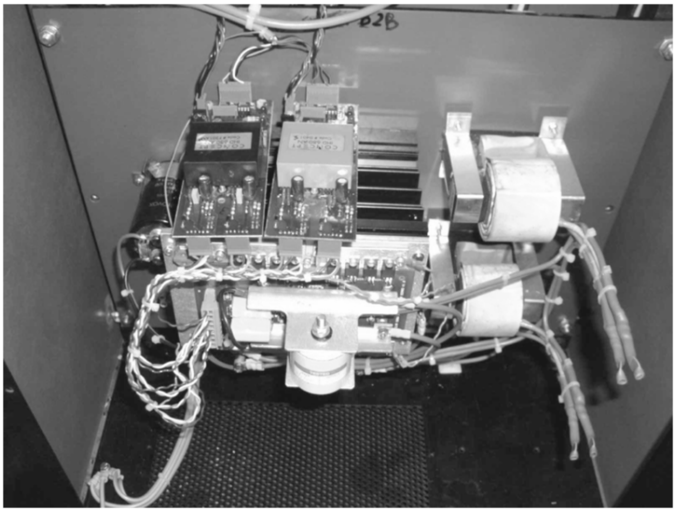

Fig. 2. Experimental H-bridge inverter module.

A. Harmonic Cancellation Scheme

In principle, for a multiinverter system, each controller could be tuned to achieve a different harmonic profile. Harmonic cancellation would take place in the overall system and the net THD level would be reduced. To force this to happen, however, inter-inverter communications would be required, a feature which is not desirable on cost grounds. An alternative approach is therefore considered, which is to arrange for the tuning within each inverter to be adjusted automatically with a random component. This will result in a harmonic output spectrum that varies with time but is uncorrelated with the harmonic spectrum of any other inverter in the system. As a consequence, the net harmonics from all the inverters will undergo a degree of cancellation while each individual inverter THD will remain almost constant. Thus, the overall system of inverters yields a net improvement in power quality.

III. EXPERIMENTAL ARRANGEMENT AND RESULTS

Three experimental, low voltage, H-Bridge inverter modules have been constructed in order to test a parallel-connected inverter system. One of these inverter modules is shown in Fig. 2. All three inverters are mounted inside a specially built cabinet and may be operated in parallel, or independently.

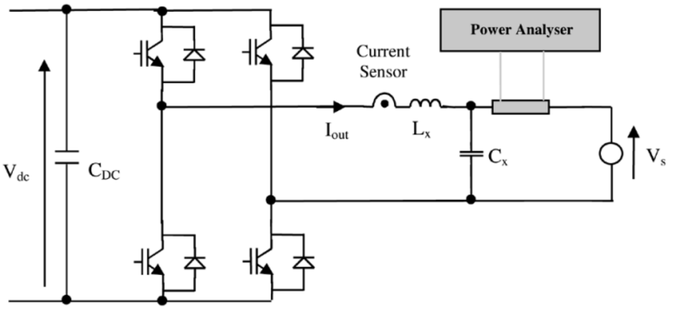

Fig. 3. Experimental H-bridge inverter. Single inverter grid connected system.

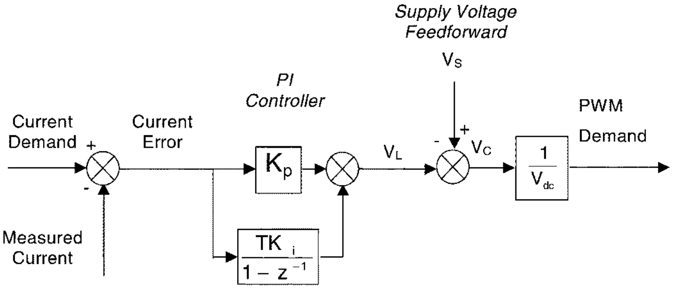

Fig. 4. Inverter current control scheme: PI with terminal voltage feed-forward control.

A. Experimental Results With Conventional Current Control Techniques

Initially, each inverter is operated independently as a single grid connected unit with a conventional current control loop. Each inverter operates from an independent 50-V dc bus, and is connected to a 20-Vrms ac grid voltage (Fig. 3). Harmonic data is acquired through the use of a power analyzer, which is capable of calculating and displaying harmonic spectra and THD information. The power analyzer is set up to acquire the harmonic data over 16 fundamental current cycles, utilising a Hanning sampling window. This is in keeping with recommended methods for measurement and interpretation of harmonic information [17]. All harmonic and THD results presented in this paper are acquired under these conditions.

Each H-Bridge is switched with a unipolar switching PWM scheme at 20 kHz. A proportional-integral (PI) current control loop (Fig. 4), with supply voltage feed-forward, is implemented with a 50-μs current sampling interval. The PWM output is scaled according to the measured dc link voltage. The controller thus compensates for any change in the dc link voltage. Each inverter is tuned independently via the software parameters: proportional gain, Kp and integral gain, Ki, to achieve the best output current fidelity possible. Each inverter is controlled to operate at unity power factor with respect to the grid voltage. This is shown in Fig. 5 for one of the experimental inverters.

Via the power analyzer, the harmonic spectrum of the output current is recorded for each inverter. The results obtained represent a snap shot in time of the performance of each inverter. To evaluate the average performance of each inverter over time, the harmonic spectrum of all three inverters is recorded at six separate intervals. An averaged harmonic spectrum is then calculated and considered to be a typical measure of inverter performance. The averaged harmonic data is imported into Microsoft Excel for presentation in graphical format.

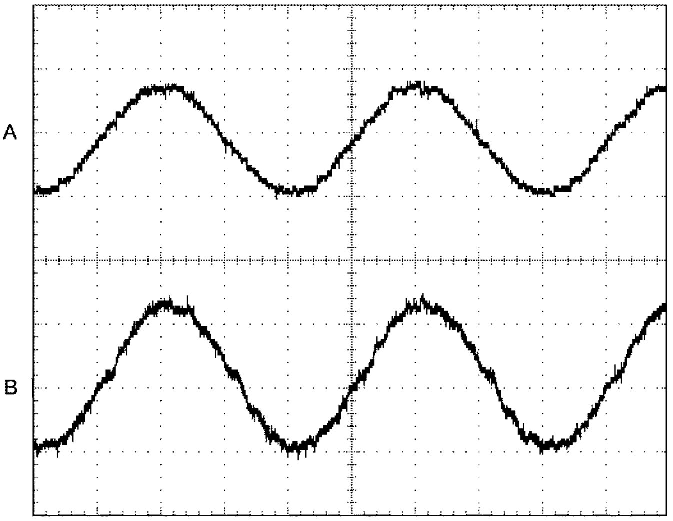

Fig. 5. Unity power factor operation of inverter 1. Time Base. 10 ms/div, Trace A: Grid voltage 30 V/div, Trace B: Inverter 1 output current 10 A/div.

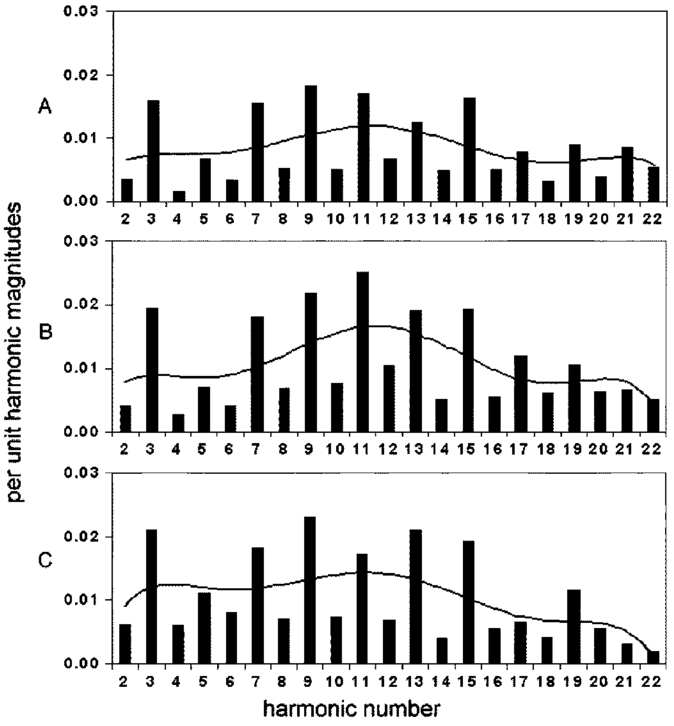

Fig. 6. Low order harmonic spectra: Inverter output current with conventional PI control. Each inverter, grid connected and operating independently. Trace A: Inverter 1, harmonic spectrum of inverter output current, Trace B: Inverter 2, harmonic spectrum of inverter output current, Trace C: Inverter 3, harmonic spectrum of inverter output current.

The averaged harmonic performance of each inverter is shown in Fig. 6. This shows the per unit magnitude of all harmonics between the second and 22nd harmonic. For all three inverters, the predominant harmonics appear between the third and the 15th harmonic. The harmonics become less of a problem beyond the 19th harmonic. This is to be expected, since the output inductor and capacitor components yield a low pass filter with an approximate 800-Hz cut off frequency.

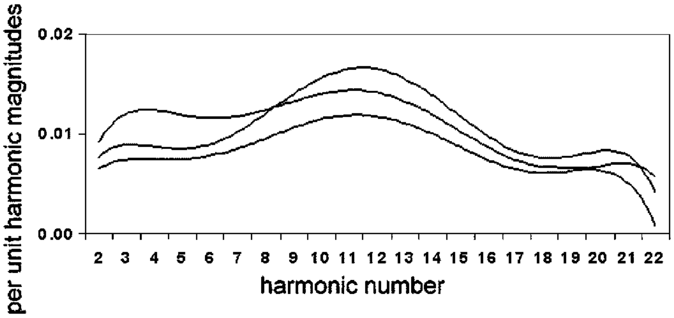

Fig. 7. Correlated harmonic trend lines for independently operated inverters, when controlled by conventional current control method.

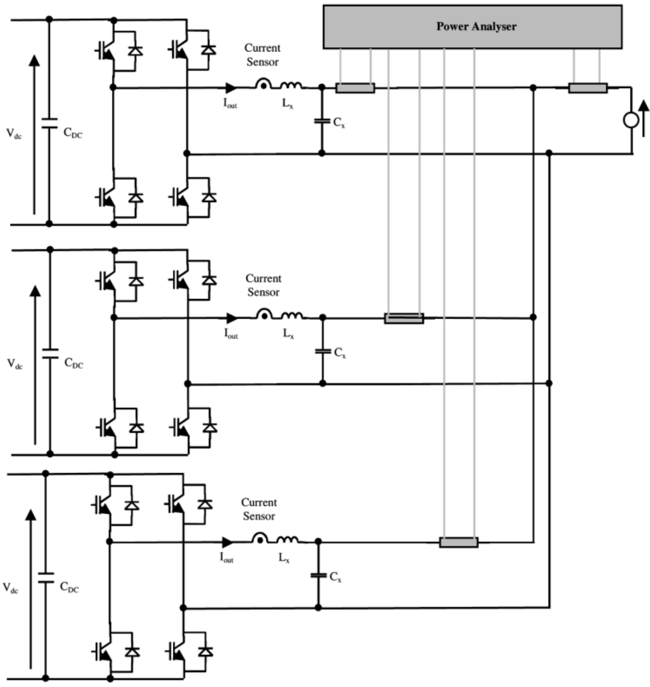

Fig. 8. Experimental, parallel connected inverter system comprising of three inverter units.

Using the Microsoft Excel trend line function, a sixth order polynomial trend line is imposed on each graph. This produces an harmonic profile for each inverter over the averaged set of harmonic data. The results show a strong correlation in harmonic profile for each of the three inverters under test. This correlation is more obviously noticed when the trend lines are superimposed on the same axis, as shown in Fig. 7.

All three inverters are then connected together at their output to form a parallel, three inverter, grid connected system as shown in Fig. 8. Each inverter is current controlled with the same controller tuning as previously determined for single inverter use. All three inverters operate at unity power factor with respect to the grid voltage. Six sets of harmonic data are collected, and once again an averaged harmonic spectrum is determined for each inverter (Fig. 9). In each case, it can be seen the largest distortion components are at the third, seventh, ninth, and 11th harmonic. Again, the resultant harmonic trend lines, shown in Fig. 10, highlight a strong correlation in harmonic profile for each of the three inverters under test. The same trend line is seen in the overall system output current, where similar harmonics dominate. This demonstrates the additive nature of the harmonics at the output from the three individual inverters. The recorded THD at the parallel inverter system output, as measured by the power analyzer, is 5.44%. It is this harmonic addition at the multiple inverter output, which is undesirable. As the number of grid connected inverter units increases, the same harmonics will continue to reinforce. This will cause problems with high levels of specific current harmonics being

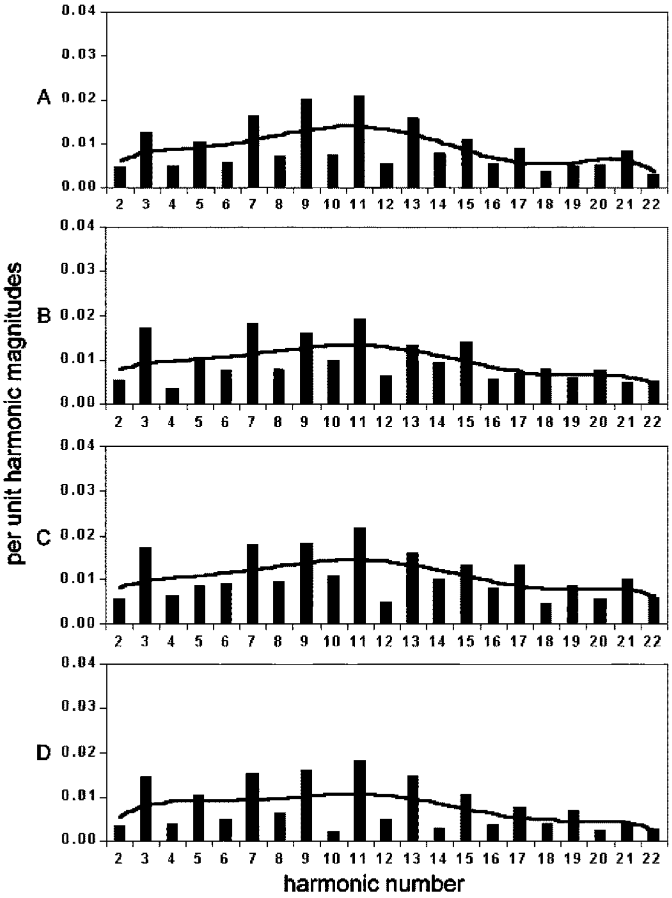

Fig. 9. Low order harmonic spectra: Inverter output current with conventional PI control. Grid connected parallel inverter system. Trace A: Inverter 1, harmonic spectrum of inverter output current, Trace B: Inverter 2, harmonic spectrum of inverter output current, Trace C: Inverter 3, harmonic spectrum of inverter output current, Trace D: Harmonic spectrum of parallel inverter system output current.

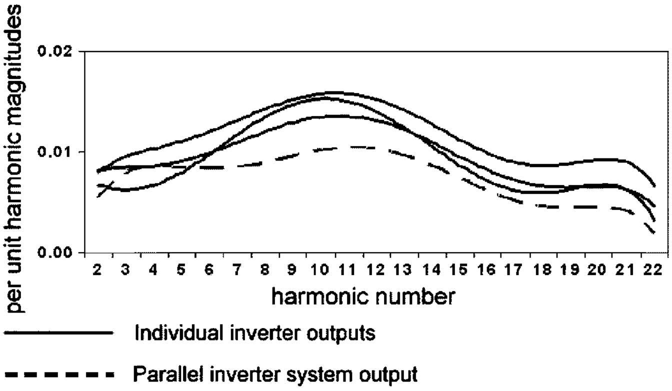

Fig. 10. Correlated harmonic trend lines for parallel inverter system, when controlled by conventional current control method.

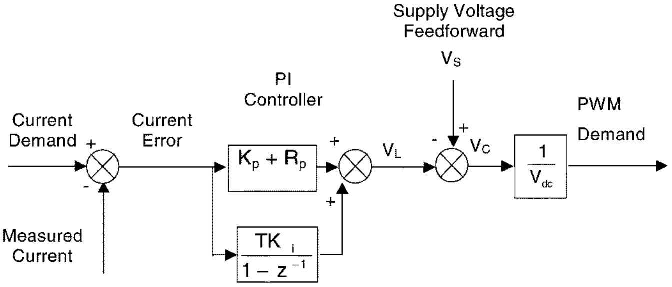

Fig. 11. Inverter current control scheme, with randomized control parameters.

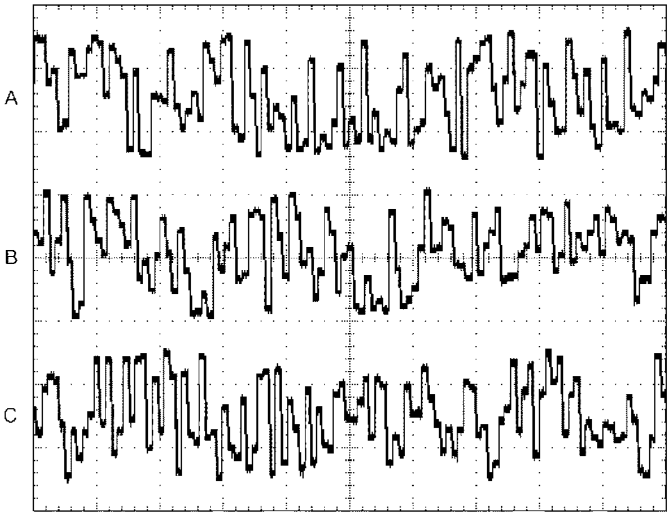

Fig. 12. Random number generator for each inverter module. Used to develop randomly varying proportional gain parameter, Time Base. 2 ms/div, Trace A: Inverter 1, random number generator, Trace B: Inverter 2, random number generator, Trace C: Inverter 3, random number generator.

injected into the grid. For this reason, randomization of the current control is considered as a method of preventing harmonic reinforcement.

B. Experimental Results With Randomized Current Control Techniques

Fig. 11 shows the modified control scheme implemented to produce un-correlated harmonic performance in each inverter. In this approach, the proportional gain of each inverter is randomly adjusted in real time. To achieve this, a random gain component, Rp is added to the already established optimum proportional gain, Kp. The random component may be a positive or negative number, but its magnitude is limited so, when added to Kp, excessive deviation from the optimal controller tuning is prevented. This creates an effective tolerance band around the optimal tuning position and is necessary to maintain acceptable current controller performance. In this instance, a ±10% tolerance band is found to be acceptable.

The random gain component, Rp, is established through the software generation of a random number. Each current controller generates a string of random numbers, which in turn produces a randomly varying signal (Fig. 12). The random number signal from each controller is then filtered through a simple three-pole digital filter, to smooth the variation in the signal. The three filtered signals, shown in Fig. 13, are then added to the fixed proportional gain in each current controller, to form a new randomly varying proportional gain parameter. This is then used in the current control of each inverter unit. Each stage of the digital filter behaves like a simple *RC* low pass filter with a cut off frequency of 400 Hz. This frequency was obtained through experimental adjustment, and was found to provide adequate performance. Further investigation into the optimum filter cut off frequency may yield improvement in performance. In general, however, it was found that too high a cut off frequency yielded a randomly varying signal with insufficient smoothing. Likewise, too low a cut off frequency limited the rate of change of the controller tuning parameter being applied to each inverter in the parallel system. Under these circumstances, less harmonic cancellation was observed at the parallel inverter system output. Fig. 14 shows the harmonic spectrum of each inverter when operated as a single inverter system. Importantly, the harmonic profile of each inverter is now different from its parallel counterparts. This is shown through the differing trend line patterns (Fig. 15) and is in contrast to the almost identical set of harmonic profiles observed with conventional current control (Fig. 7). This indicates that the random component in the current controller has successfully reduced the degree of correlation in the harmonic profile of each inverter, which is not apparent when using conventional current control methods. It is this uncorrelated performance which can be utilized to advantage in a parallel inverter system, since it yields improved opportunities for harmonic cancellation at the system output. It is worth noting that randomization of the integral gain was also seen to yield an uncorrelated harmonic profile in each inverter. However, unless a very tight tolerance band was implemented, the power factor of the inverter, with respect to the grid voltage, was subject to change. Since the inverter must operate at, or very close to, unity power factor operation with respect to the supply, only a small amount of deviation is acceptable in the integral gain.

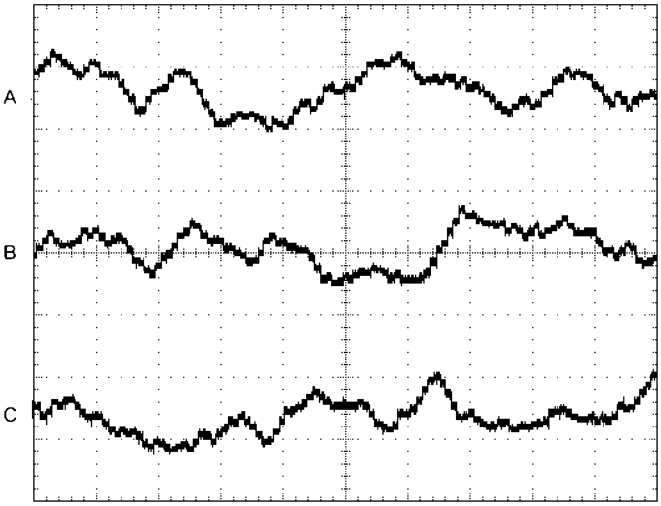

Fig. 13. Random component of proportional gain, kpr, for each inverter module. Produced by digital filtering of random number generator, Time Base: 2 ms/div, Trace A: Inverter 1, random component of proportional gain, Rp1, Trace B: Inverter 2, random component of proportional gain, Rp2, Trace C: Inverter 3, random component of proportional gain, Rp3.

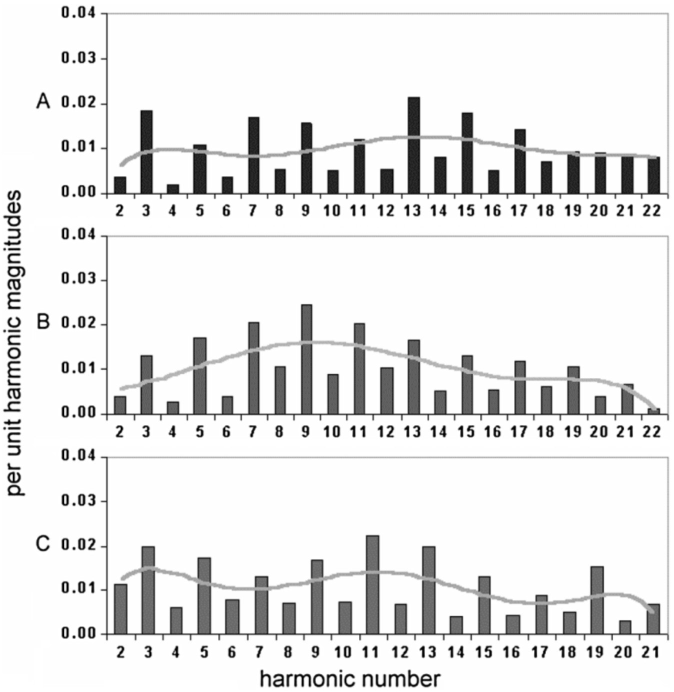

Fig. 14. Low order harmonic spectra: Inverter output current with randomized control parameters. Each inverter, grid connected and operating independently, Trace A: Inverter 1, harmonic spectrum of inverter output current, Trace B: Inverter 2, harmonic spectrum of inverter output current, Trace C: Inverter 3, harmonic spectrum of inverter output current.

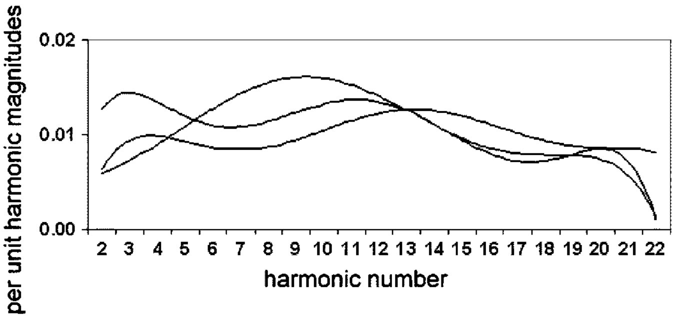

Fig. 15. Uncorrelated harmonic trend lines for individual inverters, when controlled with randomized current control method.

As such, it was considered preferential to leave this parameter unchanged.

Due to the inclusion of the controller randomization, the performance of each inverter varies with time. Therefore, a definitive assessment of the randomized control strategy cannot be determined from a single set of results taken at only one instance in time. For this reason, the performance improvement, or otherwise, of each inverter is once again determined through averaging six sets of recorded harmonic data. In this way, a statistical conclusion is made possible, based on a number of experimental results taken over time. Fig. 16 shows the harmonic spectrum, averaged over six sets of results, of each inverter when operated as a parallel inverter system with the inclusion of the randomization technique. The averaged harmonic profile of each inverter is flatter, and more evenly distributed across the harmonic range of interest than the profile recorded under conventional current control methods (Fig. 17). This is a consequence of the harmonic spectrum of each inverter varying with time. As a result, the degree of harmonic cancellation, and hence harmonic profile of the parallel inverter system output current also varies with time. Typically, the dominant harmonics in the system output current remain between the third to 11th harmonics. On average, however, the magnitude of these harmonics is often reduced. Additional reduction in the level of the higher order harmonics (above the 13th harmonic) is also noticed. Typically, on average,

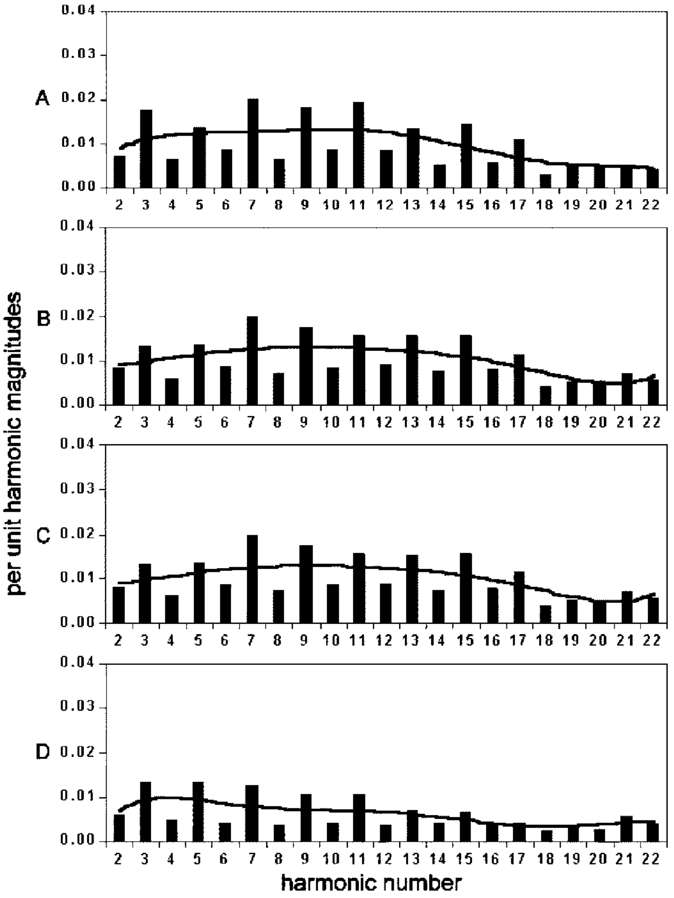

Fig. 16. Low order harmonic spectra: Inverter output current with randomized control parameters. Each inverter, grid connected and operating independently. Trace A: Inverter 1, harmonic spectrum of inverter output current, Trace B: Inverter 2, harmonic spectrum of inverter output current, Trace C: Inverter 3, harmonic spectrum of inverter output current, Trace D: Harmonic spectrum of parallel inverter system output current.

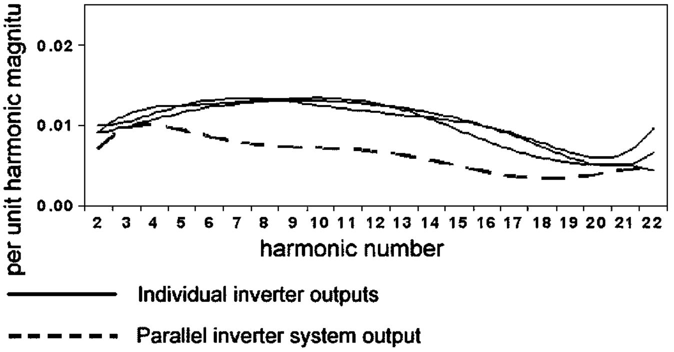

Fig. 17. Uncorrelated harmonic trend lines for parallel inverter system, when controlled with randomized current control method.

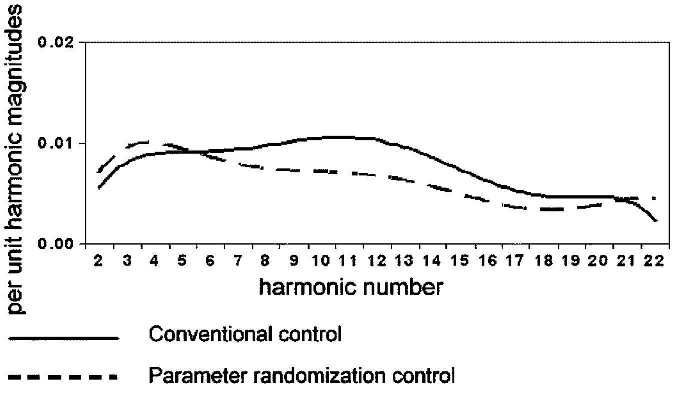

Fig. 18. Comparison of harmonic profile at parallel inverter system output, when controlled via conventional control and randomized control techniques.

a lower level of THD is observed. With the results shown, the average recorded THD measured by the power analyzer is 4.41%. This marks an appreciable improvement in the harmonic content of the parallel inverter output current, as compared to the results obtained with conventional current control. The harmonic improvement is shown more clearly in Fig. 18. The current harmonic content at the parallel inverter system output is distinctly less when controlled via the randomized control technique. In the particular result presented in Fig. 18, the magnitude of the third harmonic is actually greater than that produced by the conventional controller. This simply reflects the behavior of the controller at the instant when the result was taken. Due to the time varying nature of the parameter randomization controller, the third harmonic may be lower at a different measuring instant and a different harmonic could appear to increase in magnitude. On average, however, a lower level of THD will still be observed.

IV. CONCLUSION

In multiple grid connected inverter systems, there tends to be a high degree of correlation in the harmonic profile of each individual inverter. These harmonics, therefore, tend to be additive at the system output. Hence, the parallel inverter system output yields a harmonic spectrum, and thus THD level, which is very similar to each individual inverter unit. This paper has proposed a method of eliminating the correlation in the harmonic profile of each inverter without the need for inter-inverter communication. This has been achieved by means of randomising a tuning parameter of the current controller. The addition of a randomly varying component in the current control of each inverter has been shown to produce a harmonic output spectrum that varies with time and is uncorrelated to any other inverter in the system. By making the harmonic profile of each inverter different, the harmonics at the parallel inverter system output undergo a degree of cancellation, while the fundamental output remains the same. On average, this yields an improvement in the overall net THD of the system. In the case of the results shown, the THD is reduced from 5.44% to 4.41% representing an 18.9% improvement in THD performance. There is no cost in terms of additional system hardware required to achieve this reduction in THD level. Furthermore, the harmonic cancellation algorithm is relatively straightforward to implement in software and does not significantly add to the overall processor execution time. In a practical grid connected system, there is likely to be significantly more than three inverter units operating in parallel. By increasing the number of inverter units, the opportunity for harmonic cancellation improves. This should, theoretically, help to lower the overall THD level even further.

While primarily aimed toward grid connected inverter systems, the technique proposed is equally applicable to any parallel inverter system exhibiting correlation in individual inverter harmonic performance.

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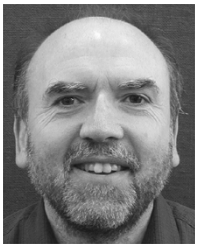

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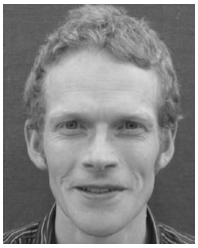

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