Power Quality Enhancement in Micro-grids Using Multifunctional DG Inverters

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Abstract—**This paper describes a digital signal processor (DSP) based flexible control scheme designed for the distributed generator (DG) inverter to perform multiple control functions. In particular the attention has been focused on the issues of power quality enhancement in micro-grids with DG inverters. The proposed control algorithm is derived from applying the Clark transformation (a-b-c to α-β) and Park transformation (α-β to d-q) to the power system parameters and the related DG control variables. With the P-Q decoupled controllers designed on the synchronously rotating d-q reference frame, the active and reactive currents injected by the DG inverter can be controlled independently. It is important to note that the new control scheme proposed in this paper does not require a conventional phase locked loop (PLL) in its control circuit and has fast dynamic response in real-time power flow regulation. The main advantage of the proposed control approach is that multiple control functions are integrated into a single DG inverter without additional sensing devices and hardware equipment. To verify the advantages and effectiveness of the control scheme, comprehensive numerical simulations and experiments on DSP based hardware setup have been carried out and typical results have been presented with brief discussions.**

Index Terms—**Digital signal processor, distributed generator, micro-grid, power quality, voltage source inverter.**

I. Introduction

In recent years, the interest in installing more distributed generators (DG) in power distribution networks has rapidly increased. A number of reasons can explain this trend; i.e. environmental concerns, electricity business restructuring, the fast developments of small scale power generation technologies and micro-grid related devices and systems. In practice, DG units can be constructed with various renewable and green energy sources; however, the real power output from these energy resources is intrinsically unstable. With the increasing number of renewable energy sources and DG installations, it is thus a crucial need to develop new control strategies for the proper operation and management of new power grid embedded with DG and micro-grid units in order to maintain or even to improve the overall reliability and quality. It is well known that power electronics technology plays an important role in DG and micro-grid operations in which the effective integration of renewable energy sources into the power grid is its major objective [1]-[6]. In the open literature, a huge number of DG application examples can be found. A standalone power generation system based on the fuel cell system was reported in [7]-[9], some typical solar cell DG systems were designed in [10], [11] and a DG system based on wind power generator was presented in [12]. In addition, as the penetration level of DG and the number of grid-tied micro-grids are increasing the reactive power compensation and power quality problems have become vital issues in the control of distribution systems. Reactive current increases the distribution system losses, limits the active power transfer capability, reduces the system power factor, and can even cause large-amplitude variations in the load-side voltage. It should be noted that in some cases fast changes in the reactive power consumption of large loads can cause voltage amplitude oscillations. This might also lead to a change in system real power demand resulting in power oscillations [13]-[15]. Although the main objective of DG in micro-grid systems is to provide active power; nonetheless, by means of power electronic systems with properly designed control schemes, reactive power can be compensated and DG systems can also provide additional control functions, such as active power filters (APF) if the power rating of the DG inverter is allowed. Theoretically, DG systems can be connected to the micro-grid network in series or in shunt; however, because the target compensated quantities; e.g. reactive power or harmonics, are direct related to the currents, shunt type topology is more realistic as it can effectively injects compensating currents at the point of common coupling (PCC). Therefore, the shunt type DG inverter is used in this paper for theoretical analysis and design of related controllers. In practical applications, the three-phase voltage source inverter (VSI) has been widely used for interfacing between DG and micro-grid networks. To achieve a multi-functional DG inverter (MDGI), the command signals for the VSI, which are current signals in nature, may include the information of active power supplied from renewable energy sources and reactive power required to compensate the voltage fluctuation at load-side as well as harmonic currents. In this paper, the hysteresis current control algorithm is used for its fast dynamic response, accurate performance and ease of implementation. As mentioned previously, to realize a simple, cost-effective and high-performance MDGI system the phase locked loop (PLL) is not used in the proposed control circuit. The performance of the proposed control scheme is firstly simulated using PSIM software and followed by a set of tests on DSP based hardware implementations. The results are presented and briefly discussed to demonstrate the feasibility and effectiveness of the proposed control scheme.

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II. Micro-grid and Control Techniques

A. Micro-grid Concepts

A basic micro-grid architecture is shown in Fig. 1. It consists of a group of radial feeders, which could be part of a distribution system or a building's electrical system. There is a static switch (SS) installed at the point of connection to the utility grid which is controlled to separate the micro-grid from a faulty utility grid in less than a cycle. In a micro-grid, some feeders may form a number of distinct zones with various sensitive loads, e.g., Load1, Load2 (A)-(B) as shown in Fig. 1 which may require local DG on renewable energy sources (RES) and certain energy storage systems. The non-critical load feeder (Load3) is normally not equipped with any local generation. As can be seen in Fig. 1, the PV INVERTER is used to demonstrate the proposed MDGI concept and Zone1 to Zone3 can be islanded from the grid using the SS if so desired.

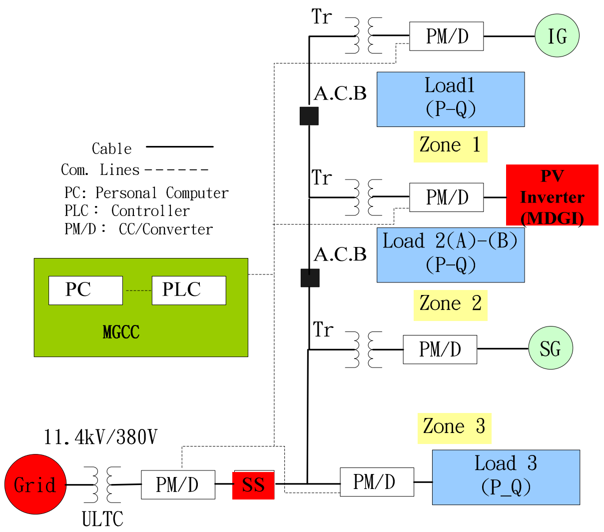

Fig. 1. Simple system diagram of a micro-grid with various DG inverters.

B. Control Techniques

As mentioned in the introduction, the current control techniques of VSI presented in this paper is based on analysis of voltage and current vector components in a special d-q reference frame. To decompose voltage and current components in a rotating reference frame, calculation of instantaneous angle of voltage or current is needed. Various phase-angle detecting methods have already been developed and reported. To obtain this angle, a PLL is commonly used in voltage source inverter's control loop [16]-[22]. It should be noted that using PLL has some disadvantages; such as problems due to synchronization of DG with the grid and elimination of a wide range of frequencies which is not favorable in DG applications, especially when the function of active power filter is activated. In addition, PLL is very sensitive to noises and disturbances. In the proposed control algorithm, instantaneous angle of load voltage is calculated directly by decomposing voltage vector components in a rotating reference frame. Removing PLL from control circuit of voltage source inverter introduces a simple control method for DG systems. In this paper, with the proposed d-q method the synchronization problem can be resolved and a better dynamic response of DG inverter can be achieved.

C. Calculation of Reference Current Commands

The derivation of mathematical models of the nonlinear shunt DG link is based on the equivalent circuit shown in Fig. 2. To achieve a reliable control, voltage and current components are firstly obtained in a stationary reference frame and related mathematical manipulations are presented as follows:

$$v_a - L\frac{di_a}{dt} - i_a R - e_a = 0 \tag{1}$$

$$v_b - L\frac{di_b}{dt} - i_b R - e_b = 0 \tag{2}$$

$$v_c - L\frac{di_c}{dt} - i_c R - e_c = 0 \tag{3}$$

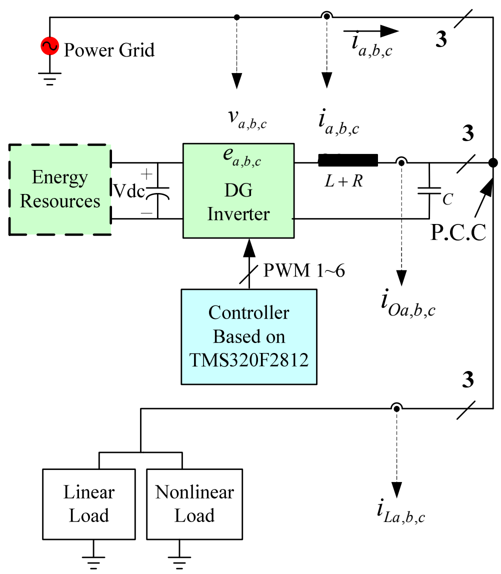

Fig. 2. A test system with DG inverter systems and control signals.

Assuming a balanced three-phase system, one can define the following two matrices:

$$P = \begin{bmatrix} \cos\theta & \cos(\theta-120°) & \cos(\theta+120°) \\ -\sin\theta & -\sin(\theta-120°) & -\sin(\theta+120°) \end{bmatrix} \tag{4}$$

$$p^{-1} = \frac{2}{3}\begin{bmatrix} \cos\theta & -\sin\theta \\ \cos(\theta-120°) & -\sin(\theta-120°) \\ \cos(\theta+120°) & -\sin(\theta+120°) \end{bmatrix} \tag{5}$$

Then, the transformations between a-b-c and d-q frames can be performed using the following equations.

$$v_{dq} = p v_{abc} \tag{6}$$

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$$i_{dq} = p i_{abc} \tag{7}$$

$$v_{abc} = p^{-1} v_{dq} \tag{8}$$

$$i_{abc} = p^{-1} i_{dq} \tag{9}$$

Using (1)-(7), one can easily have the following d-q model.

$$\begin{bmatrix} v_d \\ 0 \end{bmatrix} - L\frac{d}{dt}\begin{bmatrix} i_d \\ i_q \end{bmatrix} - \omega L\begin{bmatrix} -i_q \\ i_d \end{bmatrix} - R\begin{bmatrix} i_d \\ i_q \end{bmatrix} - \begin{bmatrix} e_d \\ e_q \end{bmatrix} = 0 \tag{10}$$

Equivalently,

$$e_d = -(Ri_d + L\frac{di_d}{dt}) + \omega L i_q + v_d \tag{11}$$

$$e_q = -(Ri_q + L\frac{di_q}{dt}) - \omega L i_d \tag{12}$$

It is clear that to calculate the injected current components of DG system to the grid, the related current and voltages signals must be transformed to synchronously rotating reference frame, i.e., in d-q components. In this transformation d-axis vector is normally assumed in the same direction as the voltage vector. With this consideration, vertical component of voltage (q-component of voltage) in rotating synchronous reference frame is always zero. Fig. 3 and 4 respectively show the voltage and current components in stationary and rotating synchronous reference frames. Transformation matrices based on Park and Clark equations are given in (6)-(9) and (13)-(16).

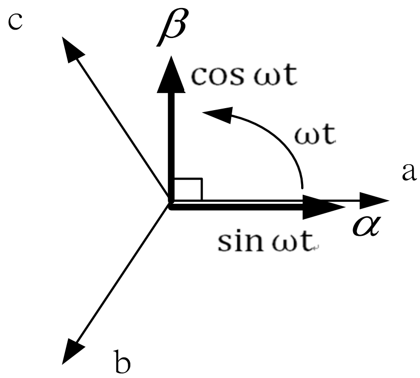

Fig. 3. The voltage and current components in stationary reference frames.

$$\begin{bmatrix} i_{ld} \\ i_{lq} \end{bmatrix} = \begin{bmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{bmatrix}\begin{bmatrix} i_{l\alpha} \\ i_{l\beta} \end{bmatrix} \tag{13}$$

$$\begin{bmatrix} v_d \\ v_q \end{bmatrix} = \begin{bmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{bmatrix}\begin{bmatrix} v_\alpha \\ v_\beta \end{bmatrix} \tag{14}$$

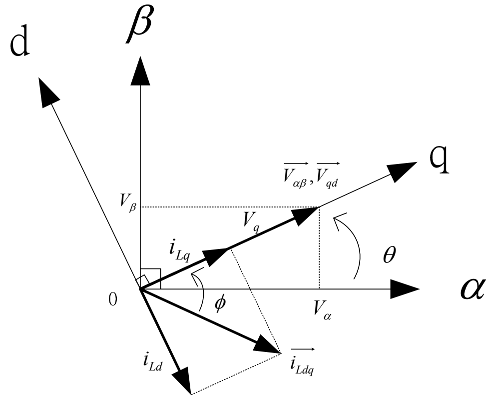

Fig. 4. The voltage and current components in rotating synchronous reference frames.

$$\theta = \tan^{-1}\frac{v_\beta}{v_\alpha} \tag{15}$$

According to Fig.4, the d-component of voltage in stationary and rotating synchronous reference frame can be calculated as:

$$v_d = \left|\vec{v}_{dq}\right| = \left|\vec{v}_{\alpha\beta}\right| = \sqrt{v_\alpha^2 + v_\beta^2} \tag{16}$$

and the load currents in d-q frame are,

$$\begin{bmatrix} i_{ld} \\ i_{lq} \end{bmatrix} = \frac{1}{v_d}\begin{bmatrix} v_\alpha & v_\beta \\ -v_\beta & v_\alpha \end{bmatrix}\begin{bmatrix} i_{l\alpha} \\ i_{l\beta} \end{bmatrix} \tag{17}$$

Similarly, one can use the following simplified equations to directly obtain the grid voltage and load currents in d-q frame.

$$\vec{v} = \sqrt{2/3}\begin{bmatrix} 1 & 1/2 \\ 0 & \sqrt{3}/2 \end{bmatrix}\begin{bmatrix} v_{ab} \\ v_{bc} \end{bmatrix} \tag{18}$$

and,

$$\begin{bmatrix} i_{ld} \\ i_{lq} \end{bmatrix} = \sqrt{2}\begin{bmatrix} \sin(\theta + \pi/3) & \sin\theta \\ \cos(\theta + \pi/3) & \cos\theta \end{bmatrix}\begin{bmatrix} i_{la} \\ i_{lb} \end{bmatrix} \tag{19}$$

Calculation of the load currents in d-q reference frame by (13), (17) or (19) makes it possible to separate fundamental and harmonic currents if there is any. Using a proper low-pass filter, the current commands can be separated into DC and alternative components as:

$$\begin{bmatrix} i_{ld}^* \\ i_{lq}^* \end{bmatrix} = \begin{bmatrix} i_{ld,DC}^* + i_{ld,h} \\ i_{lq,DC}^* + i_{lq,h} \end{bmatrix} \tag{20}$$

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It follows that one can have the following overall current control signals in d-q frame.

$$\begin{bmatrix} i_{cd}^* \\ i_{cq}^* \end{bmatrix} = \begin{bmatrix} i_{ld,DC(DG)}^* + i_{ld,h} \\ i_{lq,DC(DG)}^* + i_{lq,h} \end{bmatrix} \tag{21}$$

In (19), i_{cd}^* and i_{cq}^* are d-q current commands for the DG inverter. $i_{ld,DC(DG)}^*$ and $i_{lq,DC(DG)}^*$ are used to control respectively the desired output real and reactive power of the DG inverter, while $i_{ld,h}$ and $i_{lq,h}$ are respectively the harmonic components of d-axis and q-axis load currents to be compensated if the APF function is activated.

The α and β components of the d-q current commands can then be obtained as:

$$\begin{bmatrix} i_{c\alpha}^* \\ i_{c\beta}^* \end{bmatrix} = \frac{1}{v_d} \begin{bmatrix} v_\alpha & -v_\beta \\ v_\beta & v_\alpha \end{bmatrix} \begin{bmatrix} i_{cd}^* \\ i_{cq}^* \end{bmatrix} \tag{22}$$

Finally, the overall current commands for the DG inverter can be reached as follows.

$$i_c^* = \begin{bmatrix} i_{ca}^* \\ i_{cb}^* \\ i_{cc}^* \end{bmatrix} = \mathrm{T}^{-1} \begin{bmatrix} i_{c\alpha}^* \\ i_{c\beta}^* \end{bmatrix} \tag{23}$$

In the open literature, many current control methods for three phase systems have been proposed. Among them, a current control scheme using hysteresis regulator is used in this paper. The typical advantages of hysteresis current control are its simplicity in implementation and the fast dynamic response of its current loop.

III. Case Studies and Results

To investigate the detailed dynamics of the DG inverter system and to validate the proposed DSP based multi-functional control scheme, a set of simulations based on a simple distribution network connected with a nonlinear DG link as shown in Fig. 2 is firstly carried out in PSIM environment. It is considered that for the whole period of simulations the local loads are fed by both the main source of the power grid and the DG. During simulation process active power which is delivered from DG link is considered in three cases, i.e., zero output, with the output just the same as that of the local loads and with the output higher than that of the local load demand. This assumption makes it possible to evaluate the capability of DG link to track the fast change in the real and reactive power required by the load independently. To simulate a specific operation scenario, a fixed load type and real power demand are assumed and the harmonic distortion of current waveform are calculated and compared in various control conditions. Since the principle of proposed current control technique is based on separating active and reactive current components in rotating synchronous reference frame known as the d-q components, in all conditions only phase-a parameters (including voltage and current) are shown. To demonstrate the performance of the proposed DG inverter in compensating total load harmonic currents, source current, load current and the output current of the DG are shown simultaneously. The following part of the paper presents the details of simulation cases for various output real power from the DG.

A. Simulation Results

In this simulation case, the DG link is connected to the network at t=0.0 sec. At this moment a full-wave AC/DC converter with the output of 100V/50W is added to PCC and it is removed at t=0.05 sec. Fig.5, Fig.6 and Fig.7 respectively show the related currents in various DG operating conditions. After the connection of DG link the source current becomes sinusoidal and the harmonic currents are fully provided by the DG link, as shown in Fig.5. In Fig. 6, the nonlinear load demand is fully provided by the DG with an output real power set to 50W. As shown in Fig.7, when the output power of the DG is increased to 200W there is a real power about 150W feeding backward to the power grid.

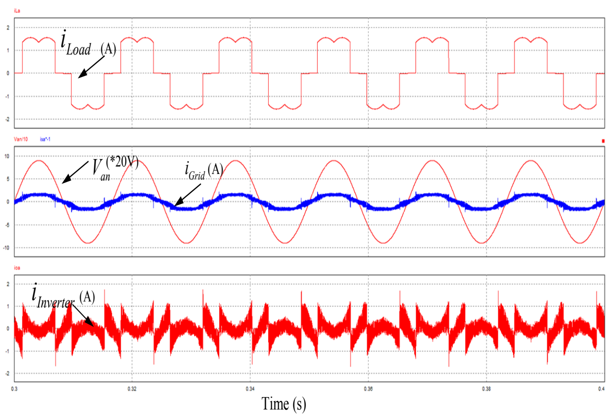

Fig.5. The grid phase-a voltage, current waveforms of load, source and the harmonic currents provided by the DG inverter (P_DG=0W).

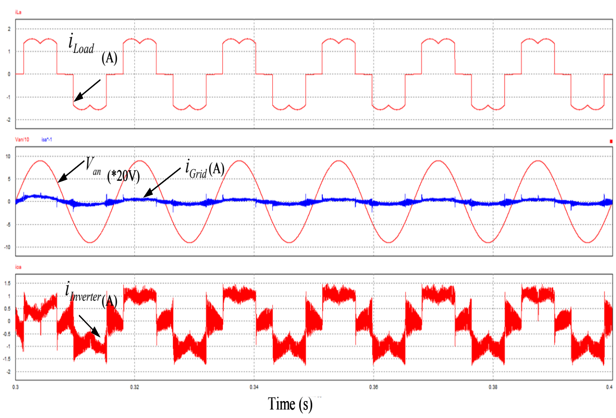

Fig.6. The grid phase-a voltage, current waveforms of load, source and the harmonic currents provided by the DG inverter (P_DG=50W).

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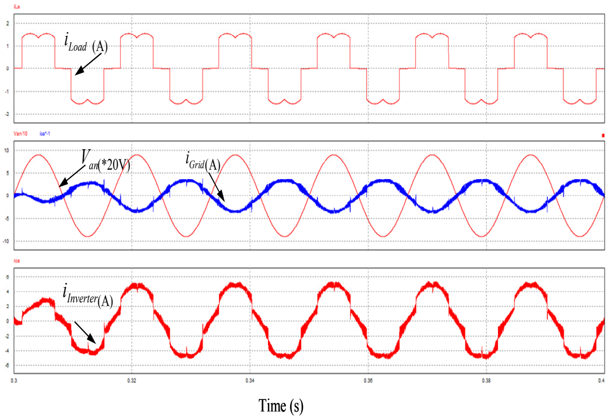
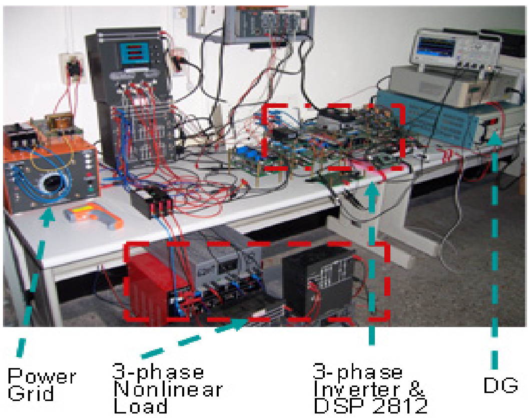


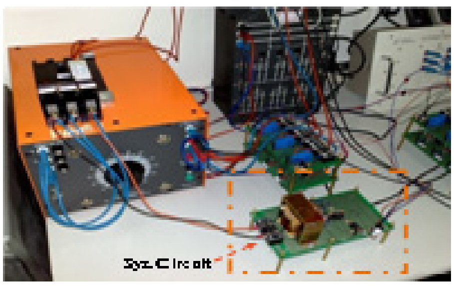
Fig. 7. The grid phase-a voltage, current waveforms of load, source and the harmonic currents provided by the DG inverter (P_DG=200W).

B. Experimental Tests and Results

In this study, the proposed control scheme is experimentally tested as configured in Fig. 8 (a) and (b). In the hardware setup, a digital controller based three phase grid-connected inverter and a set of nonlinear load module are used. Test conditions and parameters are the same as that used in simulation studies. All controllers proposed in this paper are implemented with TI DSP2812. The sensed currents and voltages acquired to the DSP and the control signals output to the driving circuit are using home-made signal acquisition circuits. Both of the sampling frequency and the switching frequency are set at 24 kHz. Fig. 9 to Fig. 11 respectively shows a set of experimental results regarding the measured voltages and currents shown in the previous simulation studies.



(a) Overall system



(b) The synchronous circuit

Fig. 8. The experimental setup of the DSP based DG inverter system.

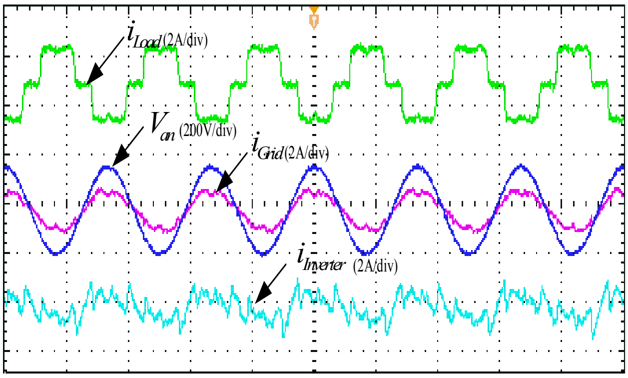


Fig. 9. The measured grid phase-a voltage, current waveforms of load, source and the harmonic currents provided by the DSP controlled DG inverter (P_DG=0W).

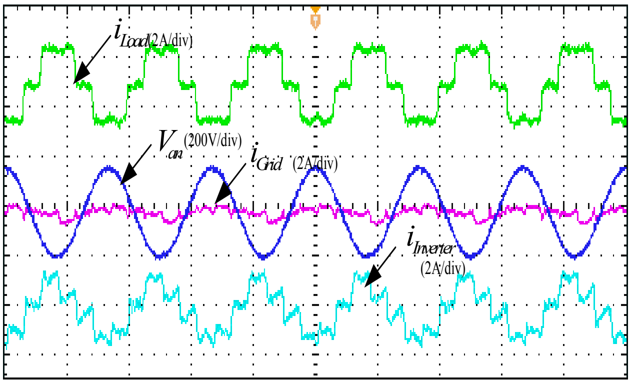


Fig. 10. The measured grid phase-a voltage, current waveforms of load, source and the harmonic currents provided by the DSP controlled DG inverter (P_DG=50W).

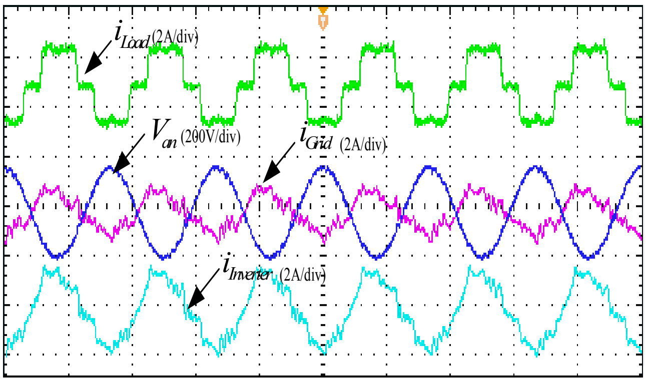


Fig. 11. The measured grid phase-a voltage, current waveforms of load, source and the harmonic currents provided by the DSP controlled DG inverter (P_DG=200W).

IV. CONCLUSION

This paper has presented a novel DSP based multi-functional control scheme for a conventional DG inverter to perform various control functions without additional sensing devices or hardware equipment. Due to the sensitivity of PLL to noises and distortions, its elimination can bring benefits for robust control against possible distortions. It is important to note that the proposed d-q axis current control method has fast dynamic response in tracking harmonic current variations since the control loops of active and reactive current components are considered independent. Using the proposed DSP based control method, besides the

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basic real power control function the DG inverter system can also be considered as a new alternative for performing functions of a D-STATCOM and a distributed APF in power distribution networks. Both experimental and simulation results indicate that the proposed DG inverter system can provide the required compensating currents in all conditions. The feasibility and effectiveness of the proposed control concept have been fully verified.

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