A Novel Compensation Current Control Method for Grid-Connected PV Inverter to Improve Power Quality in Micro-Grid

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***Abstract*—This paper presents a new control method for grid-connected pulse width modulation (PWM) inverters to reduce the output current harmonic distortion in a wide range of grid-connected distributed generation applications, including photovoltaic (PV) inverter. The proposed control method is designed to eliminate harmonics in micro-grid and to correct the system unbalance. The proposed technique is able to increase the inverter output current around 18 times of conventional one. Another advantage of the proposed control method is that it can be easily adopted into the distributed generation (DG) control system without the installation of extra hardware. The proposed control method comprises of the advance synchronous reference frame method (ASRF).**

***Keywords*—Distributed generation (DG), photovoltaic (PV), micro-turbine (MT), power quality, three-phase grid-connected inverter.**

I. Introduction

At present, the utility grid is growing towards more decentralized architectures and operation, therewith decreasing dependence on centralized power plants. An encouraging decentralized power architecture is the micro-grid (MG), which usually involves different kinds of distributed generation sources (DGSs). MGs are local distribution grids, which include three important parts such as DGSs, power electronics and control strategies [1]. Severe power quality problems have been brought by an increase of DGSs, e.g., photovoltaic (PV) systems and micro-turbine (MT) systems, as well as the nonlinear loads. Traditionally, The DGSs are normally connected to the utility grid through the grid-connected pulse width modulation (PWM) inverters which supply the active and reactive powers to the main grid [2]. Besides the generation of real power, these inverters can improve the power quality of the grid through control strategies. One problem in MGs is the total harmonic distortion (THD) of the interface inverters for current exchanged with the grid [3]. Active power filter (APF) has been proven as a flexible solution for compensating the harmonic distortion caused by various nonlinear loads in power distribution power systems. Hybrid compensation (HC) has the advantages of both passive and active filters for improving power quality problems, but it is not cost-effective. Traditionally, the interface inverters used in MGs behaved as current sources when they are connected to the main grid [4]. The primary goal of a power-electronic interface inverter is to control the power injection. However, compensation for the power quality problem, such as current harmonics, can be achieved through appropriate control strategies. Consequently, the control of DGs must be improved to meet the requirements when connected to the grid [5].

The methods in these studies ([6] and [7]) have been proposed to compensate for current harmonics in grid-connected MGs. The proposed current controller is designed in the advanced synchronous reference frame (ASRF) and is composed of a proportional–integral (PI) controller and a repetitive controller (RC), as discussed in the literature [6]. The other study [7] for the cascaded current and voltage control strategy has been proposed for the interface converter in MGs. M. Hamzeh et al. [8] proposed a control strategy, including a multi proportional resonant controller (MPRC) with adjustable resonance frequency and a harmonic impedance controller (HIC). The application of the active power filters as efficient interface for power quality improvement in distribution networks is gaining more attention with the advances in power electronics technology [9]. However, the high cost of investment, poor performance under severe unbalanced and nonlinear load conditions are the main challenges associated with active power filters. Hence, it is important to introduce an improved control scheme to enhance the power quality of the power system.

In this study, a new current compensation control method for grid-connected inverters is presented. The focus of the present paper is the current quality at PCC, namely, the reduction of THD at the PCC and MG. Another advantage of the proposed control method is that it can be easily adopted into the DG control system without the installation of extra hardware.

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II. The Proposed Control Method

To enhance grid and MG currents quality, an advanced current control method for the grid-connected inverter, as shown in Figure 1, is introduced.

Injecting a harmonic distortion, which is equivalent to a distortion caused by non-linear loads but with an opposite polarity, into the system can lead to correction of the waveform into a sine wave. Voltage distortion results from harmonic current emissions in the system impedance. Various control methods are based on the frequency domain or the time domain. Figure 2 shows a general schematic of the SRF control.

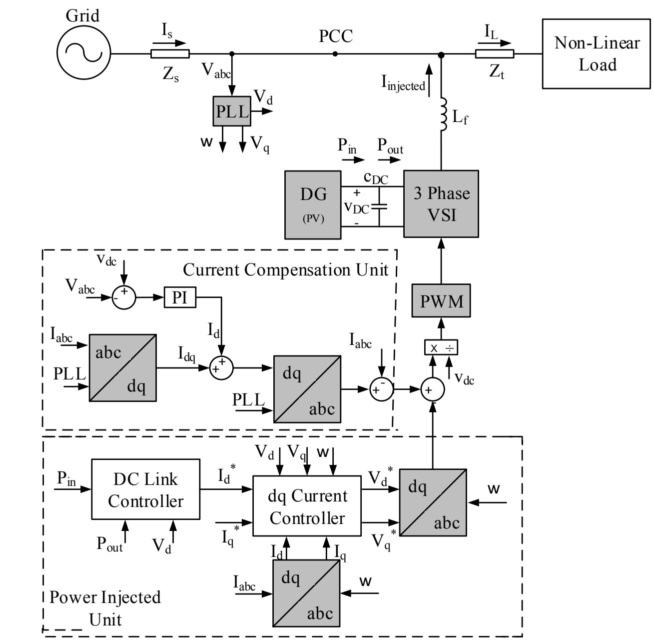


Fig. 1. Block diagram of the proposed control method

The ASRF control is also called the dq control and is used to control the grid-connected inverter in this paper. The control strategy applied to the interface Inverter usually includes two cascaded loops. An external voltage loop controls the dc-link voltage, and a fast internal current loop regulates the grid current.

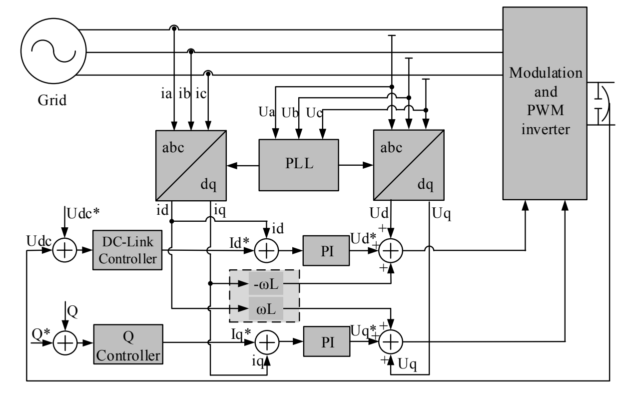


Fig. 2. General structure for synchronous rotating frame control.

The current loop is designed for current protection and power quality issues; hence, harmonic compensation is an important property of the current controller. The Park transformation for an electrical power system analysis was extended. The application of the Park transformation to three generic three-phase quantities supplies their components in $dq0$ coordinates. In general, three phase voltages and currents are transformed into $dq0$ coordinates by matrix $[L]$ as follows:

$$\begin{bmatrix} u_d \\ u_q \\ u_0 \end{bmatrix} = [L] \begin{bmatrix} u_A \\ u_B \\ u_C \end{bmatrix} \; and \; \begin{bmatrix} i_d \\ i_q \\ i_0 \end{bmatrix} = [L] \begin{bmatrix} i_A \\ i_B \\ i_C \end{bmatrix} \tag{1}$$

$$[L] = \sqrt{\frac{2}{3}} \begin{bmatrix} \sin\alpha & \sin\left(\alpha - \frac{2\pi}{3}\right) & \sin\left(\alpha + \frac{2\pi}{3}\right) \\ \cos\alpha & \cos\left(\alpha - \frac{2\pi}{3}\right) & \cos\left(\alpha + \frac{2\pi}{3}\right) \\ \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{bmatrix} \tag{2}$$

The three-phase load currents are transformed in $dq0$ coordinates by $[L]$:

$$\begin{bmatrix} i_{Ld} \\ i_{Lq} \\ i_{L0} \end{bmatrix} = [L] \begin{bmatrix} i_{LA} \\ i_{LB} \\ i_{LC} \end{bmatrix} \tag{3}$$

Therefore, through averaging i_{Ld} and i_{Lq} in domain $[0-2\pi]$ as achieved component of i_{Ld} and i_{Lq}. That is:

$$\bar{i}_{Ld} = \frac{1}{2\pi} \int_0^{2\pi} i_{Ld} \, d\,\omega t \tag{4}$$

$$\bar{i}_{Lq} = \frac{1}{2\pi} \int_0^{2\pi} i_{Lq} \, d\,\omega t$$

where

$$i_{Ld} = \sqrt{\frac{2}{3}} \left[i_{LA} \sin\omega t + i_{LB} \sin\left(\omega t - \frac{2\pi}{3}\right) + i_{LC} \sin\left(\omega t + \frac{2\pi}{3}\right) \right] \tag{5}$$

$$i_{Lq} = \sqrt{\frac{2}{3}} \left[i_{LA} \cos\omega t + i_{LB} \cos\left(\omega t - \frac{2\pi}{3}\right) + i_{LC} \cos\left(\omega t + \frac{2\pi}{3}\right) \right] \tag{6}$$

with compered (17) and (4), it can be written that

$$a_{A1}^{(i)} = \sqrt{\frac{2}{3}}\bar{i}d\left(t\right) and\ b_{A1}^{(i)} = \sqrt{\frac{2}{3}}\bar{i}q(t) \tag{7}$$

Equation (7) gives the relationship between the dc components of i_{Ld}, i_{Lq}, the coefficients of i_{LS} and the compensating objective of the propose control method. Substituting (7) into (13) gives i_{LS}, and substituting i_{LS} into (16) gives i_{PM} with i_L known. Here, i_{LS} and i_{PM} are calculated in abc coordinates.

The three-phase load Voltage are transformed into $dq0$ coordinates as follows:

$$\begin{bmatrix} u_d \\ u_q \\ u_0 \end{bmatrix} = \left[L\right] \begin{bmatrix} u_A \\ u_B \\ u_C \end{bmatrix} \tag{8}$$

Similarly, the averages of u_d and u_q are calculated, and the coefficients of u_A are as follows:

$$a_{A1}^{(u)} = \sqrt{\frac{2}{3}}\bar{u}d\left(t\right) and\ b_{A1}^{(u)} = \sqrt{\frac{2}{3}}\bar{u}q(t) \tag{9}$$

Hence, the control variables can be determined with this equation as follows:

$$v_d = \frac{2}{3}\begin{pmatrix} u_A \sin \omega t + u_B \sin(\omega t - \frac{2\pi}{3}) + \\ u_C \sin(\omega t + \frac{2\pi}{3}) \end{pmatrix} \tag{10}$$

$$v_d = \frac{2}{3}\begin{pmatrix} u_A \cos \omega t + u_B \cos(\omega t - \frac{2\pi}{3}) + \\ u_C \cos(\omega t + \frac{2\pi}{3}) \end{pmatrix} \tag{11}$$

$$v_0 = \frac{1}{3}(v_A + v_B + v_C) \tag{12}$$

Thus, the control variables become dc values; consequently, filtering and controlling can be easily achieved.

In grid-connected inverter, the proposed method is responsible for the correction of the system imbalance and the cancellation of the harmonics. Hence, after compensation, the load currents became the following:

$$i_{LS} = \begin{bmatrix} i_{LSA} \\ i_{LSB} \\ i_{LSC} \end{bmatrix} = \begin{bmatrix} a_{A1}^{(i)} \sin \omega t + b_{A1}^{(i)} \cos \omega t \\ a_{b1}^{(i)} \sin(\omega t - \frac{2\pi}{3}) + b_{b1}^{(i)} \cos(\omega t - \frac{2\pi}{3}) \\ a_{c1}^{(i)} \sin(\omega t + \frac{2\pi}{3}) + b_{c1}^{(i)} \cos(\omega t + \frac{2\pi}{3}) \end{bmatrix} \tag{13}$$

Equation (13) is the compensating objective of the propose method. The proposed method corrects the system imbalance. Therefore, the following is true:

$$a_{A1}^{(i)} = a_{B1}^{(i)} = a_{C1}^{(i)} \tag{14}$$

$$b_{A1}^{(i)} = b_{B1}^{(i)} = b_{C1}^{(i)} \tag{15}$$

In practice, the objective of the proposed method is to determine the optimum compensation. The proposed method provided the compensating currents. Thus, the following can be observed:

$$i_{PM} = i_L - i_{LS} \tag{16}$$

The norm of i_{PM} is explained as follows:

$$i_{PM} = \sqrt{i_{LA} - i_{LSA}^{\ 2} + i_{LB} - i_{LSB}^{\ 2} + i_{LC} - i_{LSC}^{\ 2}} \tag{17}$$

Because i_L and i_{LS} are usually deemed as vectors in the inner space $L^2\left[0, 2\pi\right]$. Using the best approximation theorem in inner space, the optimum compensating objective i_{LS} is given as (14), in which the following equations apply:

$$a_{A1}^{(i)} = \frac{\int_0^{2\pi} \begin{bmatrix} i_{LA} \cos \omega t + i_{LB} \cos\left(\omega t - \frac{2\pi}{3}\right) \\ + i_{LC} \cos\left(\omega t + \frac{2\pi}{3}\right) d\omega t \end{bmatrix}}{3\pi} \tag{18}$$

$$b_{A1}^{(i)} = \frac{\int_0^{2\pi} \begin{bmatrix} i_{LA} \sin \omega t + i_{LB} \sin\left(\omega t - \frac{2\pi}{3}\right) \\ + i_{LC} \sin\left(\omega t + \frac{2\pi}{3}\right) d\omega t \end{bmatrix}}{3\pi}$$

The values of $a_{b1}^{(i)}$, $a_{c1}^{(i)}$, $b_{B1}^{(i)}$ and $b_{C1}^{(i)}$ can be calculated using (14) and (15). The substitution of (18) in (16) gives the reference currents of the proposed control method. Compensation will be performed by the proposes control method if in the power system, the three-phase voltages are sinusoidal, as follows:

$$u_A = a_{A1}^{(u)} \sin \omega t + b_{A1}^{(u)} \cos \omega t \quad (19)$$

$$u_B = a_{b1}^{(u)} \sin(\omega t - \frac{2\pi}{3}) + b_{b1}^{(u)} \cos(\omega t - \frac{2\pi}{3}) \quad (20)$$

$$u_C = a_{c1}^{(u)} \sin(\omega t + \frac{2\pi}{3}) + b_{c1}^{(u)} \cos(\omega t + \frac{2\pi}{3}) \quad (21)$$

where

$$a_{A1}^{(u)} = a_{B1}^{(u)} = a_{C1}^{(u)} \; and \; b_{A1}^{(u)} = b_{B1}^{(u)} = b_{C1}^{(u)} \quad (22)$$

The dc-link voltage in this structure is controlled by the essential output power, which is the reference for the active current controller [5]. Typically, the *dq* control methods are associated with proportional–integral (PI) controllers because they have a satisfactory behavior when regulating *dc* variables. Equation (23) gives the matrix transfer function in *dq* coordinates:

$$G_{PI}^{(dq)}(s) = \begin{bmatrix} K_p + \frac{K_i}{s} & 0 \\ 0 & K_p + \frac{K_i}{s} \end{bmatrix} \quad (23)$$

where K_p and K_i are the proportional and integral gain of the controller, respectively.

Furthermore, the phase-locked loop (PLL) technique can be used to provide the phase information of the grid voltage, which is required to generate the current reference, i_{ref} . Using a PLL system, the three current references are created, each with the error going into the controller, and the corresponding measured current can be compared. Accordingly, if hysteresis or dead-beat controllers are employed in the current loop, then the modulator is no longer necessary. It is noteworthy that the output of these controllers is the switching states for the switches in the interface inverter. When three PI controllers are used, the modulator is essential for creating the duty cycles for the PWM pattern.

III. System Configuration

In a basic micro-grid architecture (Figure 3), the electrical system is assumed to be radial with several feeders and a collection of loads.

This MG includes four DGs, such as the micro-turbine (MT), the fuel cell (FC), wind turbine (WT) and photovoltaic array (PV) which are connected to the grid by the interface inverter.

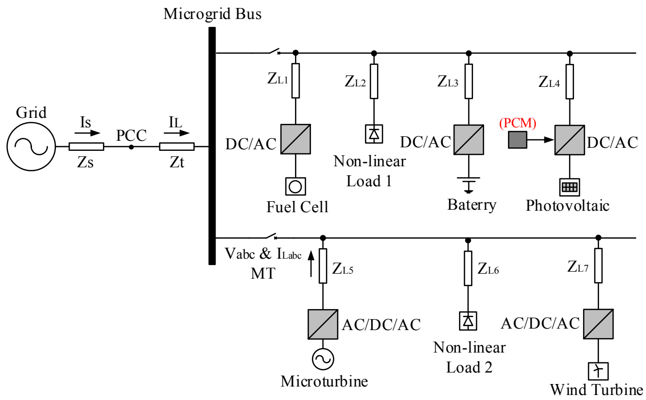


Fig. 3. Study system configuration.

The proposed control method is applied to the PV; however, the FC and MT are connected to the grid by the ordinary interface inverter without the control strategy. The WT are connected to the grid by the interface inverter with the *dq* control strategy.

The parameters of the three-phase power line [10] can be found in Table 1.

TABLE I. Power Line Parameters

	Z_{L1}	Z_{L2}	Z_{L3}	Z_{L4}	Z_{L5}	Z_{L6}	Z_{L7}	Lt	Ls
R(Ω)	0.2	0.5	0.7	0.2	0.1	0.2	0.2	-	-
L(mH)	0.6	1.3	1.9	0.2	0.3	0.6	1.5	0.1	0.01

Figure 4 shows the structure of an ASRF method control for a control interface converter PV without the compensation current. The control method parameters are listed in Table 3. In this system, a fuel cell with an output of 50 kW and a grid-connected PV array with an output of 100 kW are connected to the grid via inverters with the proposed control method. A 9 MW wind farm is also connected to the grid by AC/DA/AC converter.

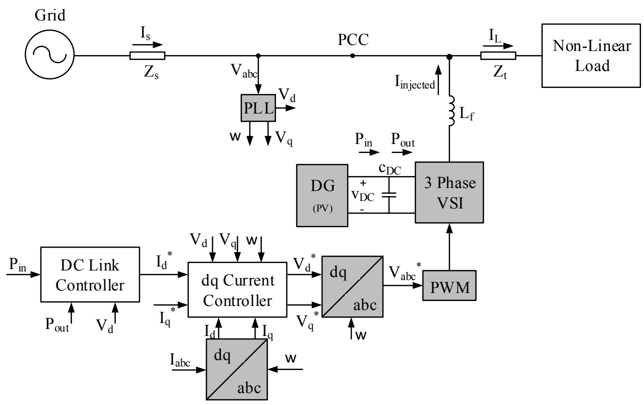


Fig. 4. Block diagram of the control interface converter of the micro-turbine.

The system also consists of two non-linear loads, such as the three unbalanced single-phase diode rectifiers and the three-phase diode rectifier, which produced the distorted waveform. In the micro-grid, the voltage is assumed to be sinusoidal.

TABLE II. PROPOSED CONTROL PARAMETERS

Controller	Parameter value
V_{dc} (V)	688
Proportional gain (K_p)	0.4
Integral gain (K_i)	10
Fundamental Frequency (H_z)	50
V_{abc} (V) and $V_{abc\ DG}$ (V)	220
I_{abc} (A)	260

IV. SIMULATION RESULTS

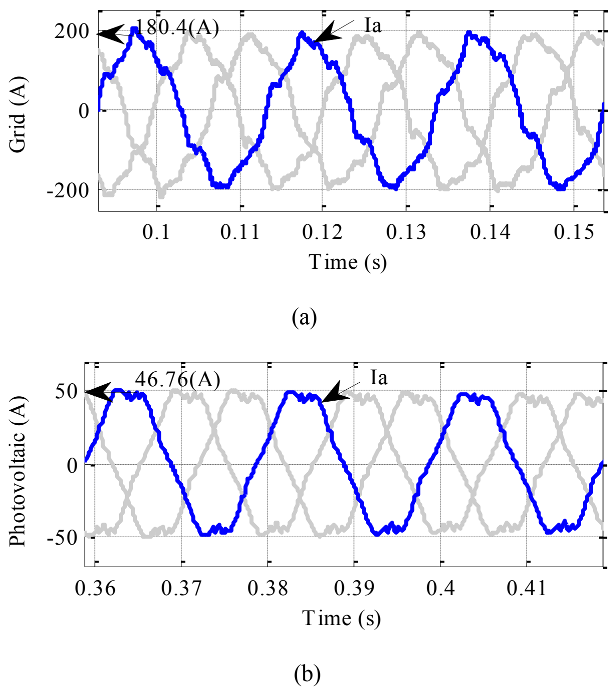
To demonstrate the effectiveness of the proposed control strategy, the system in Figure 3 was simulated in MATLAB/Simulink. In the simulation, two case studies are taken into account.

Case study I: Without any compensation.

Case study II: Harmonic compensation without compensation devices just with the proposed control method.

A. Case study I

In this case study, the resulting system waveforms are shown in Figure 5 without any compensation devices. DG sources and nonlinear loads make the system current non-linear and unbalanced.



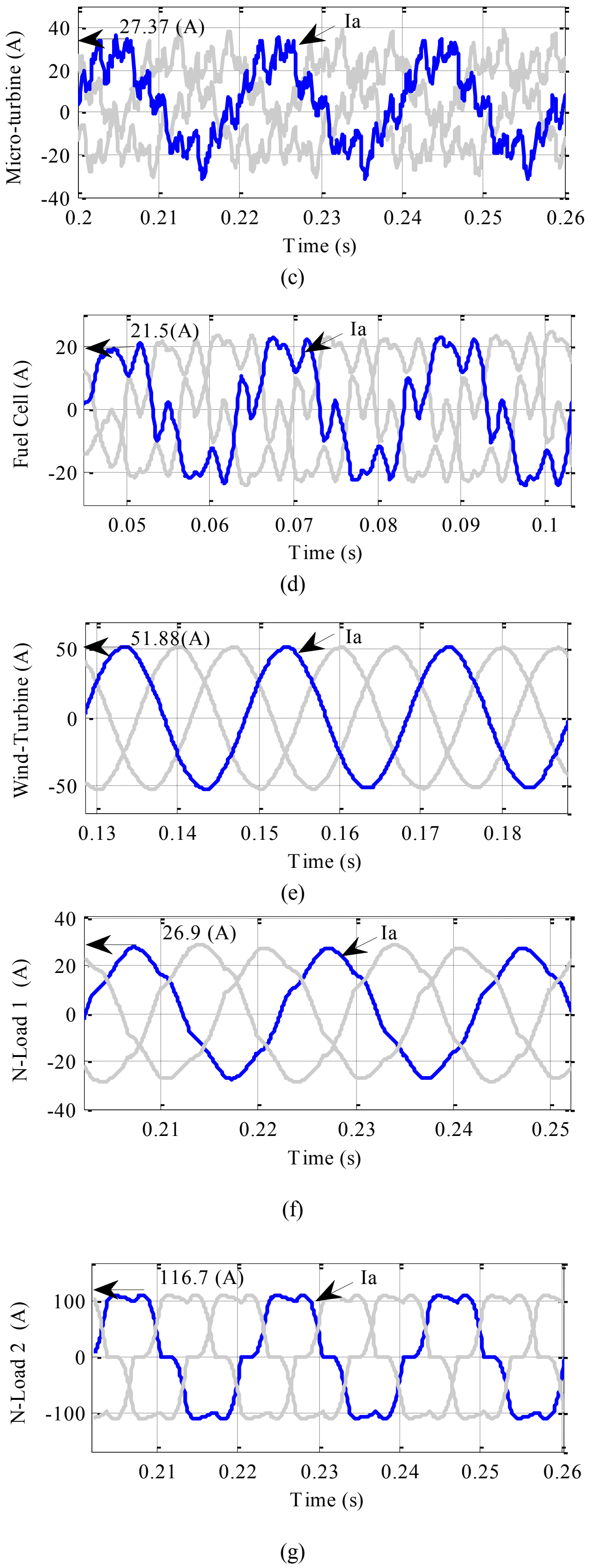
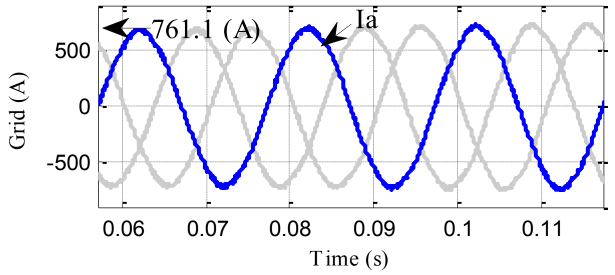


Fig. 5. Grid, DG units and nonlinear load current waveforms without any compensation: (a) Grid currents; (b) PV currents; (c) MT currents; (d) FC currents; (e) WT currents; (f) nonlinear load 1 currents and (g) nonlinear load 2 currents.

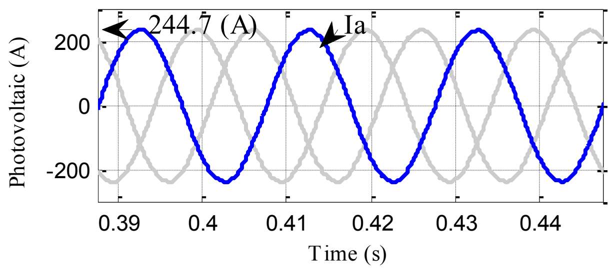
The Current and THD value of study system in case study I (before compensation) can be found in Tables 3.

B. Case study II

This case study has an improved power quality with the absence of compensation devices such as passive filter and active power filter in the MG. The main contribution of this study are the PCC and MG currents compensation. The compensated system currents are explained in this subsection. Figures 6 (a) and (b) show the effective compensation values of the harmonic current for the system and the DG unit (PV), respectively. This case study shows that the proposed control method can compensate for the current system (PCC current) and DGs without the power compensation devices.



(a)



(b)

Fig. 6. Grid and DG unit current waveforms with propose control method; (a) system currents; (b) Photovoltaic.

When all of the loads and DGs are connected, the THD current without any compensation was 12.97%. As shown in Figure 6(a), THD is reduced to 1.55% in the proposed control method. The simulation results of Figures 6 (b) shows the performance of the proposed control method to compensate the distorted waveform of Figures 5 (b). Consequently, it is capable of meeting the IEEE 519-1992 recommended harmonic standard limits.

The Current and THD value of study system in case study II, with the proposed control method is given in Table 3.

TABLE III. CURRENT AND THD RESULTS

	Before Compensation		With Proposed Control Method	
	Current (A)	THD %	Current (A)	THD %
Grid	180.4	**12.97**	761.1	**1.55**
PV	46.76	**8.25**	244.7	**1.07**

MT	27.37	37.08	-	-
FC	21.6	39.26	-	-
WT	51.88	1.4	-	-
N-load1	26.9	6.64	-	-
N-Load2	116.7	18.12	-	-

V. CONCLUSION

This study proposes a new control strategy for harmonic current compensation for photovoltaic inverters in a MG. The proposed control method utilizes advance synchronous reference frame method. When nonlinear, unbalanced loads and DGs are connected to the grid, the proposed strategy significantly and simultaneously improves the THD of the interface inverter for DGs and the grid current. This strategy can be used for single-phase and three-phase systems. The simulation results verify the feasibility and effectiveness of the newly designed control method for a grid-connected inverter in a MG.

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