

Active Harmonic Filtering Using Current-Controlled, Grid-Connected Dg Units with Closed-Loop Power Control

Parsaveni.Manasa*, N.Mahender **

*(Power Electronics, M.tech, JNTU university
Email: Manasacutty@gmail.com)

** (Power Electronics, M.tech, JNTU University, Hyderabad
Email: Mahendereed@gmail.com)

Abstract :

The increasing application of nonlinear loads may cause distribution system power quality issues. In order to utilize distributed generation (DG) unit interfacing converters to actively compensate harmonics, an enhanced current control approach, which seamlessly integrates system harmonic mitigation capabilities with the primary DG power generation function? The current controller has two well-decoupled control branches to independently control fundamental and harmonic DG currents, local nonlinear load harmonic current detection and distribution system harmonic voltage detection are not necessary for the harmonic compensation method. Moreover, a closed-loop power control scheme is employed to directly derive the fundamental current reference without using any phase-locked loops(PLL).The power control scheme effectively eliminates the impact of steady-state fundamental current tracking errors in the DG units. An accurate power control is realized even when the harmonic compensation functions are activated.

Keywords:- Active power filter, distributed generation, harmonic compensation, harmonic extraction, phase-locked loop (PLL), resonant controller, and virtual impedance.

I. INTRODUCTION

Due to the growing importance of renewable-energy-based power generation, a large number of power electronics interfaced DG units have been installed in the low-voltage power distribution systems [1]. It has been reported that the control of interfacing converters can introduce system resonance issues [2]. Moreover, the increasing presence of nonlinear loads, such as variable-speed drives, light-emitting diode (LED) lamps, compact fluorescent lamps (CFLS), etc., will further degrade distribution system power quality.

To compensate distribution system harmonic distortions, a number of active and passive filtering methods have been developed [3]. However, installing additional filters is not very favorable due to cost concerns. Alternatively, distribution system power quality enhancement using flexible control of gridconnected DG units is becoming an interesting topic[5]–[12], where the ancillary harmonic compensation capability is integrated with the DG primary power generation function through modifying control references. This idea is especially attractive considering that the available power from backstage renewable energy resources is often lower than the power rating of DG interfacing converters.

It is worth mentioning that the DG real and reactive power control performance shall not be

affected during the harmonic compensation. To satisfy this requirement, the fundamental DG current reference shall be calculated according to power references. Conventionally, the fundamental current reference can be determined based on the assumption of ripple-free grid voltage with fixed magnitude, and the PLL is used to synchronize the fundamental current reference with the main grid. However, considering that PoC voltage magnitude often varies due to the distribution system power flow fluctuations, this method may cause nontrivial power control errors. Alternatively, the fundamental current reference can also be calculated through the “power–current transformation” in [7], where only the detected PoC voltage fundamental component is used in the calculation.

However, for a DG unit with the ancillary harmonic compensation capability, the interactions between distorted DG current and PoC harmonic voltages may contribute some DC real and reactive power bias [31], and these power bias cannot be directly addressed in the control method in [7]. In order to ensure accurate power tracking performance, a closed-loop DG power control is necessary.

To simplify the operation ofDGunits with ancillary harmonic compensation capabilities while maintaining accurate power control, this paper proposes an improved current controller with two

parallel control branches. The first control branch is responsible for DG unit fundamental current control, and the second one is employed to compensate local load harmonic current or feeder resonance voltage. In contrast to the conventional control methods with harmonic detection, the PoC voltage and local load current can be directly used as the input of the proposed current controller, without affecting the harmonic compensation accuracy of the DG unit. Moreover, with simple PI regulation in the outer power control loop, the proposed DG unit also achieves zero steady-state power tracking errors even when the fundamental current tracking has some steady-state errors. Simulated and experimental results from a single-phase DG unit validate the effectiveness of the proposed DG control method.

II. DG UNITS WITH HARMONIC COMPENSATION

In this section, a DG unit using the compensation strategies in the conventional active power filters is briefly discussed. Afterward, a detailed discussion on the proposed control strategy is presented.

A. Conventional Local Load Harmonic Current Compensation

Fig. 1 illustrates the configuration of a single-phase DG system, where the interfacing converter is connected to the distribution system with a coupling choke (L_f and R_f). There is a local load at PoC. In order to improve the power quality of grid current (I_2), the harmonic components of local load current (I_{Local}) shall be absorbed through DG current (I_1) regulation. The DG unit control scheme is illustrated in the lower part. As shown, its current reference consists of two parts. The first one is the fundamental current reference (I_{ref-f}), which is synchronized with PoC voltage (V_{PoC}) as

$$I_{ref-f} = \frac{\cos(\theta) \cdot P_{ref} + \sin(\theta) \cdot Q_{ref}}{E^*} \quad (1)$$

where θ is the PoC voltage phase angle detected by PLL, P_{ref} and Q_{ref} are the real and reactive power references, and E^* is the nominal voltage magnitude of the system. However, the current reference generator in (1) is not accurate in controlling DG power, due to variations of the PoC voltage magnitude. To overcome this drawback, an improved power control method with consideration of PoC voltage magnitude fluctuations [11] was developed as shown in Section II-B. First, the fundamental PoC voltage $V_{PoC\alpha-f}$ and its orthogonal component $V_{PoC\beta-f}$ (quarter cycle delayed respect to $V_{PoC\alpha-f}$) are obtained by using SOGI [15] as

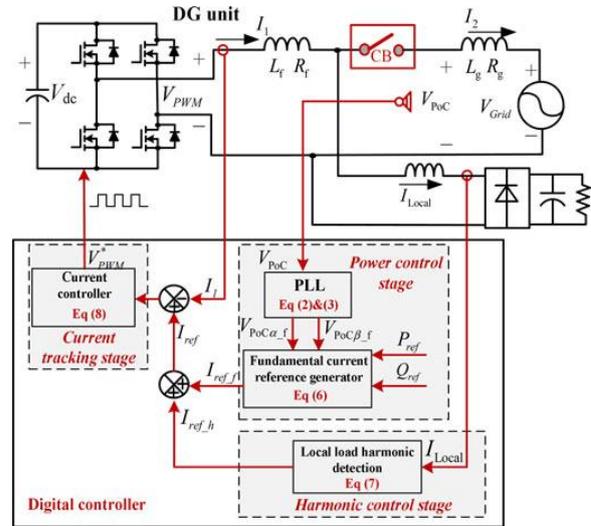


Fig. 1. DG unit with local load harmonic current compensation capability.

$$V_{PoC\alpha-f} = \frac{2\omega_{D1}s}{s^2 + 2\omega_{D1}s + \omega_f^2} \cdot V_{PoC} \quad (2)$$

$$V_{PoC\beta-f} = \frac{2\omega_{D1}\omega_f}{s^2 + 2\omega_{D1}s + \omega_f^2} \cdot V_{PoC} \quad (3)$$

where ω_{D1} is the cutoff bandwidth of SOGI and ω_f is the fundamental angular frequency.

For a single-phase DG system, relationships between the power reference and the fundamental reference current can be established in the artificial stationary $\alpha - \beta$ reference frame as follows:

$$P_{ref} = \frac{1}{2} \cdot (V_{PoC\alpha-f} \cdot I_{ref\alpha-f} + V_{PoC\beta-f} \cdot I_{ref\beta-f}) \quad (4)$$

$$Q_{ref} = \frac{1}{2} \cdot (V_{PoC\beta-f} \cdot I_{ref\alpha-f} - V_{PoC\alpha-f} \cdot I_{ref\beta-f}) \quad (5)$$

where $I_{ref\alpha-f}$ and $I_{ref\beta-f}$ are the DG fundamental current reference and its orthogonal component in the artificial $\alpha - \beta$ reference frame. Similarly, $V_{PoC\alpha-f}$ and $V_{PoC\beta-f}$ are PoC fundamental voltage and its orthogonal component, respectively.

According to (4) and (5), the instantaneous fundamental current reference (I_{ref-f}) of a single-phase DG unit can be obtained as

$$I_{ref-f} = I_{ref\alpha-f} = \frac{2(V_{PoC\alpha-f} \cdot P_{ref} + V_{PoC\beta-f} \cdot Q_{ref})}{V_{PoC\alpha-f}^2 + V_{PoC\beta-f}^2} \quad (6)$$

Moreover, to absorb the harmonic current of local nonlinear load, the DG harmonic current reference (I_{ref-h}) is produced

$$I_{ref-h} = G_D(s) \cdot I_{Local} = \sum_{h=3,5,7,9,\dots} \frac{2\omega_{D2}s}{s^2 + 2\omega_{D2}s + \omega_h^2} \cdot I_{Local} \quad (7)$$

where $G_D(s)$ is the transfer function of the harmonic extractor. To realize selective harmonic compensation performance [24], [25], $G_D(s)$ is designed to have a set of bandpass filters with cutoff frequency ω_{D2} .

With the derived fundamental and harmonic current references, the DG current reference is written as $I_{ref} = I_{ref\ f} + I_{ref\ h}$. Afterward, the proportional and multiple resonant controllers [12], [18]–[20] are adopted to ensure rapid current tracking.

$$V_{PWM}^* = G_{cur}(s) \cdot (I_{ref} - I_1)$$

$$= \left(K_p + \sum_{h=f,3,5,\dots,15} \frac{2K_{ih}\omega_c s}{s^2 + 2\omega_c s + \omega_h^2} \right) \cdot (I_{ref\ f} + I_{ref\ h} - I_1) \quad (8)$$

where V^*P is the reference voltage for pulsewidth modulation (PWM) processing, K_p the proportional gain of the current controller $G_{cur}(s)$, K_{ih} the resonant controller gain at the order h , ω_c the cutoff frequency of the resonant controller, and ω_h is the angular frequency at fundamental and selected harmonic frequencies.

B. Conventional Feeder Resonance Voltage Compensation

It should be pointed out that the objective of local load harmonic compensation is to ensure sinusoidal grid current I_2 in Fig. 1. In this control mode, DG unit should not actively regulate the PoC voltage quality. As a result, the PoC voltage can be distorted especially when it is connected to the main grid through a long underground cable with nontrivial parasitic capacitance [8], [23]. In this case, the feeder is often modeled by an LC ladder [23], [26]. To address the resonance issue associated with long underground cables, the R-APF concept can also be embedded in the DG unit current control, as illustrated in Fig. 2. Compared to Fig. 1, the DG harmonic current reference in this case is modified as

$$I_{ref\ h} = \left(-\frac{1}{RV} \right) \cdot (G_D(s) \cdot V_{PoC}) \quad (9)$$

Where RV is the virtual damping resistance at harmonic frequencies. With this harmonic current reference (9), the DG unit essentially works as a small equivalent harmonic resistor at the end of the feeder, when it is viewed at power distribution system level [33], [34]. By providing sufficient damping effects to the long feeder, the voltage quality at different positions of the feeder can be improved.

C. Proposed Harmonic Compensation Method

Note that for the local load harmonic current compensation and the PoC harmonic voltage compensation, the harmonic current is absorbed by the DG unit.

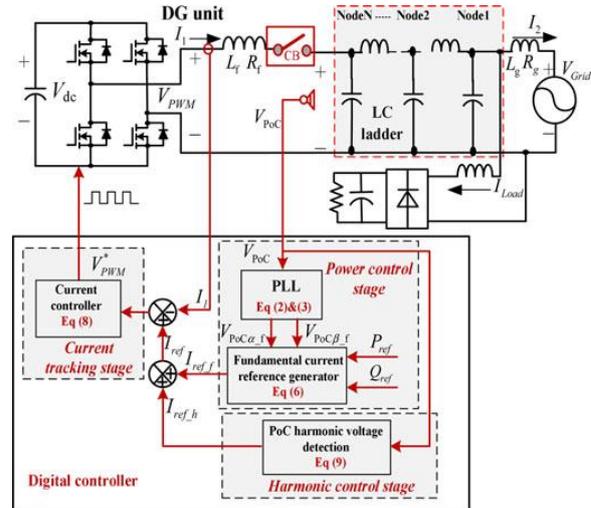


Fig. 2. DG unit with PoC harmonic voltage mitigation capability.

Consequently, interactions between DG harmonic current and PoC harmonic voltage may cause some steady-state DG power offset [31]. Nevertheless, the power control using fundamental current reference in (6) is still in an open-loop manner, which can not address the power offset introduced by harmonics interactions. In order to achieve accurate power control performance in current-controlled DG units, the instantaneous fundamental current reference (including both magnitude and phase angle information) can be determined by a simple closed-loop power control strategy as

$$I_{ref\ f} = g_1 \cdot V_{PoC\alpha} + g_2 \cdot V_{PoC\beta} \quad (10)$$

where $V_{PoC\alpha}$ is the nonfiltered PoC voltage expressed in the $\alpha - \beta$ reference frame ($V_{PoC\alpha} = V_{PoC}$) and $V_{PoC\beta}$ is its orthogonal component. The gains g_1 and g_2 are adjustable and they are used to control DG unit real and reactive power, respectively. The detailed regulation law is shown as follows:

$$g_1 = \left(k_{p1} + \frac{k_{I1}}{s} \right) \cdot \left(\frac{1}{\tau s + 1} \cdot P_{ref} - P_{DG} \right) + \frac{P_{ref}}{(E^*)^2} \quad (11)$$

$$g_2 = \left(k_{p2} + \frac{k_{I2}}{s} \right) \cdot \left(\frac{1}{\tau s + 1} \cdot Q_{ref} - Q_{DG} \right) + \frac{Q_{ref}}{(E^*)^2} \quad (12)$$

where k_{p1} , k_{I1} , k_{p2} , and k_{I2} are proportional and integral control parameters, P_{ref} and Q_{ref} are the real and reactive power references, E^* is the nominal voltage magnitude of the DG unit, τ is the time constant of first-order low-pass filters. P_{DG} and Q_{DG} are measured DG power with low-pass filtering as

$$P_{DG} = \frac{1}{2(\tau s + 1)} \cdot (V_{PoC\alpha} \cdot I_{1\alpha} + V_{PoC\beta} \cdot I_{1\beta}) \quad (13)$$

$$Q_{DG} = \frac{1}{2(\tau s + 1)} \cdot (V_{PoC\beta} \cdot I_{1\alpha} - V_{PoC\alpha} \cdot I_{1\beta}) \quad (14)$$

Where $I_1\alpha$ is the non-filtered DG current expressed in the stationary $\alpha - \beta$ frame ($I_1 = I_1\alpha$) and $I_1\beta$ is its delayed orthogonal component. Note that in (13) and (14), the power offset caused by harmonic voltage and harmonic current interactions is also considered.

Although the proposed closed-loop power control method eliminates power tracking errors, it can be seen that the fundamental current reference in (10) will be distorted if PoC voltage has some ripples. When it is applied to the current controller in (8), the distorted fundamental current reference will affect the performance of DG harmonic current tracking.

To overcome this drawback, an improved proportional and resonant controller with two control branches is proposed as

$$V_{P\text{PWM}}^* = \frac{\text{Branch1:power control}}{s^2 + 2\omega_c s + \omega_f^2} \cdot (I_{\text{ref}_f} - I_1) + \left(K_P + \sum_{h=3,5,\dots,15} \frac{\text{Branch2:harmonic control}}{s^2 + 2\omega_c s + \omega_h^2} \right) \cdot (I_{\text{ref}_h} - I_1) = G_f(s) \cdot (I_{\text{ref}_f} - I_1) + G_h(s) \cdot (I_{\text{ref}_h} - I_1) \quad (15)$$

As shown, the fundamental current reference in (10) is regulated by the “power control” branch in (15). As only fundamental resonant controller is adopted in this branch, the impacts of harmonic components in I_{ref_f} can be automatically filtered out. Therefore, the power control branch will not introduce any obvious harmonic disturbances to the harmonic control branch in (15).

Meanwhile, the harmonic current reference I_{ref_h} is regulated by the “harmonic control” branch, where only harmonic resonant controllers are included. Considering some noncharacteristic harmonics exist in the system, a small proportional gain K_P is used to ensure superior harmonic current tracking. As the fundamental resonant controller is not included in the harmonic control branch, it is possible to remove the harmonic extraction blocks in (7). Accordingly, the local load current or PoC voltage without any filtering is directly used as the input of the harmonic control branch. Note that when the harmonic current reference I_{ref_h} is set to zero, the harmonic control branch ensures that the DG current is ripple-free. This is very similar to the performance of conventional DG unit without any compensation,

where the DG unit current is controlled to be sinusoidal.

It is important to mention that grid voltage frequency variations [35] often affect the power control accuracy and the harmonic compensation performance of the DG unit. As PI controllers are used in the closed loop power control in (11) and (12), zero steady-state power control error can still be realized even when grid voltage frequency has variations. On the other hand, to alleviate the impact of frequency variation to DG harmonic current tracking accuracy, wide bandwidth (ω_c) harmonic resonant controllers should be considered in (15). Additionally, if the DG unit needs to be connected to a utility grid with nontrivial frequency variations, a frequency estimator can be adopted to detect the frequency of the grid. In this case, the detected grid frequency is used as a parameter of resonant controllers and the DG current tracking accuracy can be improved accordingly. Note that the frequency detector, such as that in [36], is simpler than a PLL, as the grid angle calculation is not needed in the proposed DG power control loop.

III. Modeling Of Dg Unit With The Proposed Current Control Scheme

In this section, the harmonic compensation performance using the proposed current controller is investigated.

A. Modeling of the Proposed Current Control Method

It is well understood that the current-controlled inverter shall be described as a closed-loop Norton equivalent circuit [27], [29]

$$I_1 = H_c(s) \cdot I_{\text{ref}} - Y_c(s) \cdot V_{\text{PoC}} \quad (17)$$

Where the gain ($H_c(s)$ and $Y_c(s)$) can be derived based on the conventional current controller in (8) and the DG unit circuitry parameters [27]. The corresponding equivalent circuit is shown in Fig. 4. Note that for the DG unit with harmonic compensation capability, the current reference I_{ref} in Fig. 4 has two components (I_{ref_f} and I_{ref_h}). For the DG unit using the proposed current control method, its equivalent circuit is derived as shown in the rest of this section. First, (18) describes the transfer function of DG unit filter plant $G_{\text{ind}}(s)$ as

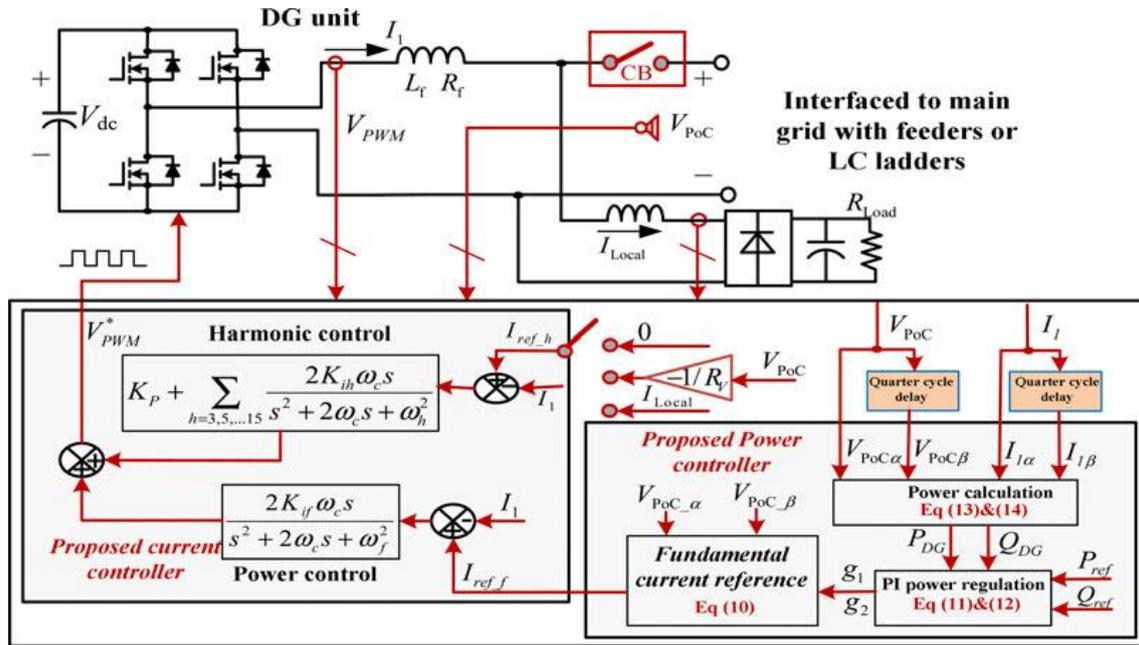


Fig. 3. DG unit with the proposed control scheme.

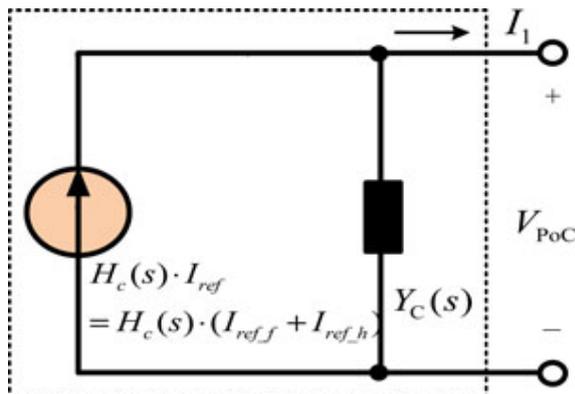


Fig. 4. Equivalent circuit of a DG unit using conventional current control method.

$$I_1 = G_{Ind}(s) \cdot (V_{PWM} - V_{PoC})$$

$$= \frac{1}{L_f s + R_f} \cdot (V_{PWM} - V_{PoC}) \quad (18)$$

Where L_f is the inductance of the DG coupling choke and R_f is its stray resistance. V_{PWM} is the average inverter output voltage. Additionally, the delay of DG control [28] is written as

$$V_{PWM} = e^{-1.5T_d \cdot s} \cdot V_{PWM}^* \quad (19)$$

Where T_d is the sampling period of the system. Note that the delay here includes one sampling period processing delay and half sampling period voltage modulation delay.

By solving (15), (18), and (19), the closed-loop DG current response can be given as

$$I_1 = H_f(s) \cdot I_{ref_f} + H_h(s) \cdot I_{ref_h} - Y_P(s) \cdot V_{PoC} \quad (20)$$

Where $H_f(s)$ and $H_h(s)$ represent the closed-loop response of DG unit current to fundamental and

harmonic current references, respectively. $Y_P(s)$ demonstrates the sensitivity of DG line current tracking to PoC voltage disturbances [27]. The detailed expression of terms in (20) is listed as

$$H_f(s) = \frac{e^{-1.5T_d \cdot s} \cdot G_f(s) \cdot G_{Ind}(s)}{1 + e^{-1.5T_d \cdot s} \cdot (G_f(s) + G_h(s)) \cdot G_{Ind}(s)}$$

$$H_h(s) = \frac{e^{-1.5T_d \cdot s} \cdot G_h(s) \cdot G_{Ind}(s)}{1 + e^{-1.5T_d \cdot s} \cdot (G_f(s) + G_h(s)) \cdot G_{Ind}(s)}$$

$$Y_P(s) = \frac{G_{Ind}(s)}{1 + e^{-1.5T_d \cdot s} \cdot (G_f(s) + G_h(s)) \cdot G_{Ind}(s)}$$

For the DG unit with the proposed current control scheme, a modified Norton equivalent circuit with two controlled current sources can be applied to demonstrate the unique behavior of the proposed controller. As illustrated in Fig. 5, the current source $H_f(s)I_{ref_f}$ is responsible for regulating DG unit fundamental current. Additionally, the current source $H_h(s)I_{ref_h}$ aims to compensate system harmonics at selected harmonic frequencies.

IV. SIMULATED RESULTS

In order to verify the correctness of the proposed control strategy, simulated results are obtained from a single-phase DG unit.

A. Simulated Results

1) Compensation of Local Nonlinear Loads:

First, the DG unit with a local diode rectifier load is tested in the simulation. The configuration of the system is the same as shown in Fig. 1, and PoC is connected to a stiff controlled voltage source (to

emulate the main grid) with nominal 50 Hz frequency. The main grid voltage contains 2.8% third and 2.8% fifth harmonic voltages. In this simulation, the reference power is set to 600W and 200 var. The detailed parameters of the system are provided in Table I. When the local load harmonic current is not compensated by the DG unit [corresponding to $I_{ref\ h} = 0$ in (15) and (16)], the performance of the DG unit is shown in Fig. 9. It can be seen from Fig. 9(b) that the DG current is sinusoidal with 5.57% total harmonic distortion (THD). At the same time, the harmonic load

currents flow to the main grid is illustrated in Fig. 9(a). Once the local load harmonic current compensation is activated by setting $I_{ref\ h} = I_{Local}$ in (16), the performance of the system is shown in Fig. 10. Although harmonic extractions are not used in this simulation, the proposed method can still realize

satisfied local load harmonic current compensation, resulted in an enhanced grid current quality with 5.88% THD. Meanwhile, DG unit current is polluted with 201.5% THD.

**TABLE I
PARAMETERS IN SIMULATION**

System Parameter	Value
Grid voltage	Simulation 230V/50Hz
DG filter	$L_f=6.5\text{mH}$, $R_f=0.15\Omega$
Grid feeder	$L_g=3.4\text{mH}$, $R_g=0.15\Omega$
LC ladder with five identical LC filter	$L=1.0\text{mH}$, $C=25\mu\text{F}$ for each LC filter
Sampling/Switching frequency	20kHz/10kHz
DC link voltage	Simulation 550V
Power Control Parameter	Value
Real power control k_{p1} , k_{i1}	$k_{p1}=0.00001$, $k_{i1}=0.001$
Reactive power control k_{p2} , k_{i2}	$k_{p2}=0.00001$, $k_{i2}=0.001$
LPF time constant τ	0.0322 Sec
Current control Parameter	Value
Proportional gain K_p	48
Resonant gains K_{rh}	1500 ($h=f$); 900 ($h=3, 5, 7, 9$); 600 ($h=11, 13, 15$)
Resonant controller bandwidth ω_c	4.1 rad/s
R_v (for PoC harmonic voltage compensation)	5 Ω

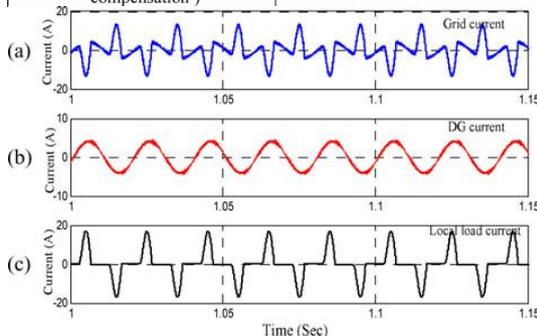


Fig. 9. Performance of the DG unit during DG harmonic rejection: (a) grid current I_2 ; (b) DG current I_1 ; (c) local load current I_{Local} .

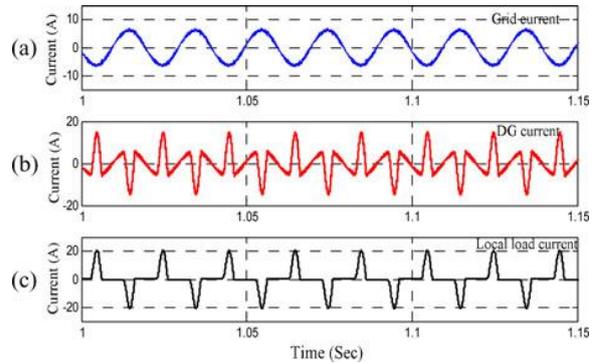


Fig. 10. Performance of the DG unit during local load compensation: (a) grid current I_2 ; (b) DG current I_1 ; (c) local load current I_{Local} .

For the DG unit operating under local load harmonic compensation mode, its fundamental current reference adjusted by (10) is shown in Fig. 11(a). As the DG unit also provides 200 var reactive power to the grid, it can be seen that the fundamental current reference is slightly lagging of the PoC voltage.

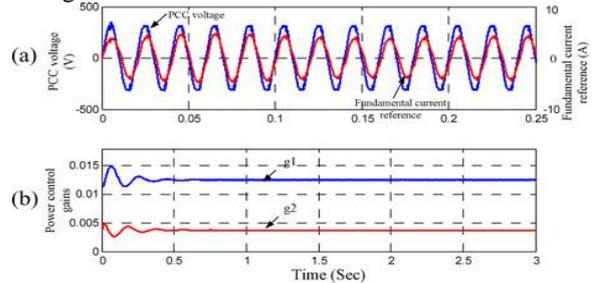


Fig. 11. Power control reference during local harmonic compensation: (a) PoC voltage and fundamental current reference $I_{ref\ f}$; (b) power control gains g_1 and g_2 .

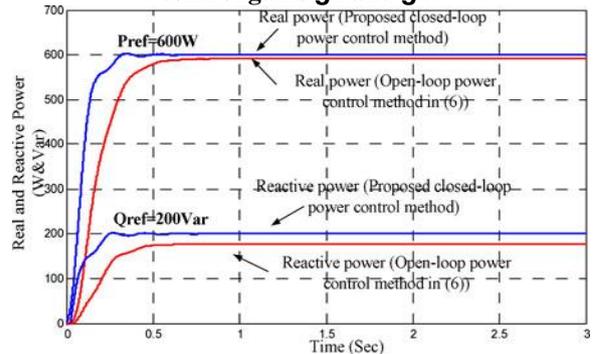


Fig. 12. Power flow of the DG unit during local load harmonic current compensation ($P_{ref} = 600$ W and $Q_{ref} = 200$ var).

The effectiveness of the proposed closed-loop power control strategy is verified in Fig. 12, where the real and reactive power is calculated by (13) and (14). When the conventional open-loop power control in (6) is applied, it can be noticed that the DG output real and reactive power control is not accurate. On the other hand, as the proposed control strategy

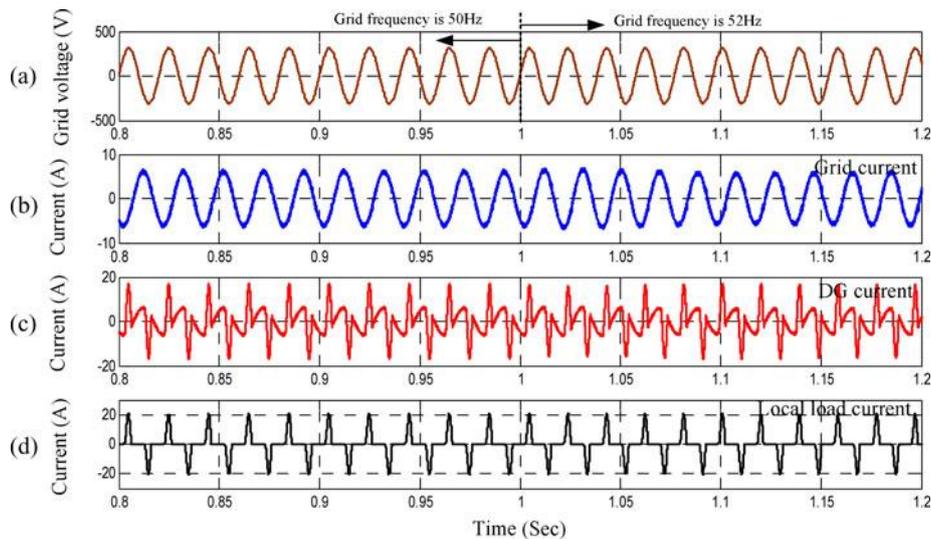


Fig. 13. Performance of the DG unit under local harmonic compensation mode (2 Hz grid voltage frequency change at 1.0 s): (a) grid voltage V_{grid} ; (b) grid current I_2 ; (c) DG current I_1 ; (d) local load current I_{Local} .

Regulates DG output power in a closed-loop manner, it guarantees zero steady-state power tracking error.

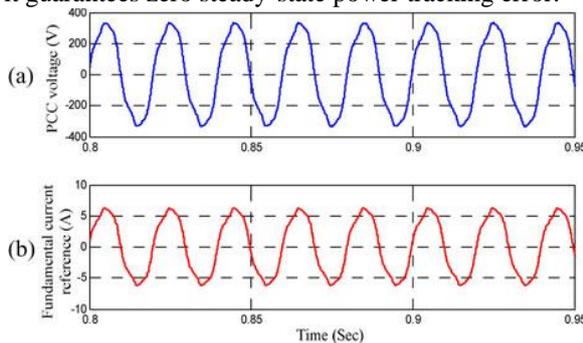


Fig. 14. PoC voltage and the fundamental current reference for DG unit during harmonic rejection: (a) PoC voltage V_{PoC} ; (b) fundamental current reference I_{ref} .

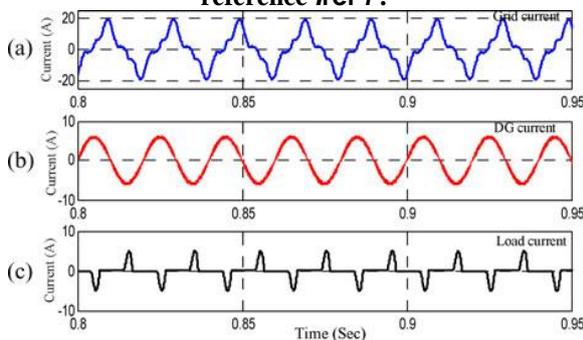


Fig. 15. Performance of the DG unit during harmonic rejection: (a) grid current I_2 ; (b) DG current I_1 ; (c) load current I_{Load} .

2) *Performance Under Frequency Disturbance:* The performance of the DG unit under grid voltage frequency deviation is also examined. In this test, the bandwidth (ω_c) of resonant controllers at harmonic

frequencies is selected as 16 rad/s. As a result, the performance of current tracking can be less sensitive to grid voltage frequency variations. In Fig. 13, the DG unit power reference is 600 W/600 var and the grid voltage frequency is fixed to 50 Hz before 1.0 s. During this time range, it can be seen that DG unit absorbs the harmonic current from local nonlinear loads and the grid current THD is only 5.05%. At the time instant 1.0 s, the grid frequency jumps to 52 Hz. In the case of grid frequency variation, it can be seen that the proposed method still maintains satisfied harmonic compensation performance with 5.99% grid current THD. It is emphasized here that in a real DG system, the frequency deviation is typically lower, e.g., for the small photovoltaic (PV) systems, the allowed frequency deviation range is -0.7 to 0.5 Hz. The DG unit needs to be disconnected from the utility when the grid frequency deviation is out of this range [35]. If very larger frequency variation is present, a frequency estimator could be used to update the PR control parameters. As discussed earlier, such a frequency estimator will be simpler than a PLL.

V. CONCLUSION

In this paper, a simple harmonic compensation strategy is proposed for current-controlled DG unit interfacing converters. By separating the conventional proportional and multiple resonant controllers into two parallel control branches, the proposed method realizes power control and harmonic compensation without using any local nonlinear load harmonic current extraction or PoC harmonic voltage detection. Moreover, the input of the fundamental power control branch is regulated by

a closed-loop power control scheme, which avoids the adoption of PLLs. The proposed power control method ensures accurate power control even when harmonic compensation tasks are activated in the DG unit or the PoC voltage changes. Simulated and experimental results from a single-phase DG unit verified the feasibility of the proposed strategy.

REFERENCES

- [1] F. Blaabjerg, Z. Chen, and S. B. Kjaer, "Power electronics as efficient interface in dispersed power generation systems," *IEEE Trans. Power Electron.*, vol. 19, no. 5, pp. 1184–1194, Sep. 2004.
- [2] F. Wang, J. L. Duarte, M. A. M. Hendrix, and P. F. Ribeiro, "Modeling and analysis of grid harmonic distortion impact of aggregated DG inverters," *IEEE Trans. Power Electron.*, vol. 26, no. 3, pp. 786–797, Mar. 2011.
- [3] L. Asiminoaei, F. Blaabjerg, S. Hansen, and P. Thogersen, "Adaptive compensation of reactive power with shunt active power filters," *IEEE Trans. Ind. Appl.*, vol. 44, no. 3, pp. 867–877, May/June 2008.
- [4] L. Asiminoaei, F. Blaabjerg, and S. Hansen, "Detection is key—Harmonic detection methods for active power filter applications," *IEEE Ind. Appl. Mag.*, vol. 13, no. 4, pp. 22–33, Jul./Aug. 2007.
- [5] N. Pogaku and T. C. Green, "Harmonic mitigation throughout a distribution system: A distributed-generator-based solution," in *IEE Proc. Gener. Transm. Distrib.*, vol. 153, no. 3, pp. 350–358, May 2006.
- [6] C. J. Gajanayake, D. M. Vilathgamuwa, P. C. Loh, R. Teodorescu, and F. Blaabjerg, "Z-source-inverter-based flexible distributed generation system solution for grid power quality improvement," *IEEE Trans. Energy Convers.*, vol. 24, no. 3, pp. 695–704, Sep. 2009.
- [7] R. I. Bojoi, G. Griva, V. Bostan, M. Guerrero, F. Farina, and F. Profumo, "Current control strategy of power conditioners using sinusoidal signal integrators in synchronous reference frame," *IEEE Trans. Power Electron.*, vol. 20, no. 6, pp. 1402–1412, Nov. 2005.
- [8] T.-L. Lee and P.-T. Cheng, "Design of a new cooperative harmonic filtering strategy for distributed generation interface converters in an islanding network," *IEEE Trans. Power Electron.*, vol. 22, no. 5, pp. 1919–1927, Sep. 2007.
- [9] B. Han, B. Bae, H. Kim, and S. Baek, "Combined operation of unified power-quality conditioner with distributed generation," *IEEE Trans. Power Del.*, vol. 21, no. 1, pp. 330–338, Mar. 2003.
- [10] M. Cirrincione, M. Pucci, and G. Vitale, "A single-phase DG generation unit with shunt active power filter capability by adaptive neural filtering," *IEEE Trans. Ind. Electron.*, vol. 55, no. 5, pp. 2093–2100, May 2008.
- [11] R. I. Bojoi, L. R. Limongi, D. Ruiu, and A. Tenconi, "Enhanced power quality control strategy for single-phase inverters in distributed generation systems," *IEEE Trans. Power Electron.*, vol. 26, no. 3, pp. 798–806, Mar. 2011.
- [12] J. He, Y. W. Li, and S. Munir, "A flexible harmonic control approach through voltage controlled DG-Grid interfacing converters," *IEEE Trans. Ind. Electron.*, vol. 59, no. 1, pp. 444–455, Jan. 2012.
- [13] B. P. Mcgrath, D. G. Holmes, and J. J. H. Galloway, "Power converter line synchronization using a discrete Fourier transform (DFT) based on a variable sample rate," *IEEE Trans. Power Electron.*, vol. 20, no. 4, pp. 877–884, Apr. 2005.
- [14] H. Akagi, Y. Kanazawa, and A. Nabae, "Instantaneous reactive power compensation comprising switching devices without energy storage components," *IEEE Trans. Ind. Appl.*, vol. 20, no. 3, pp. 625–630, Mar/Apr. 1984.
- [15] P. Rodríguez, A. Luna, I. Candela, R. Mujal, R. Teodorescu, and F. Blaabjerg, "Multiresonant frequency-locked loop for grid synchronization of power converters under distorted grid conditions," *IEEE Trans. Ind. Electron.*, vol. 58, no. 1, pp. 127–138, Jan. 2011.
- [16] J. Miret, M. Castilla, J. Matas, J. M. Guerrero, and J. C. Vasquez, "Selective harmonic-compensation control for single-phase active power filter with high harmonic rejection," *IEEE Trans. Ind. Electron.*, vol. 56, no. 8, pp. 3117–3127, Aug. 2009.
- [17] D. A. Toerrey and A. M. A. M. Al-Zamel, "Single-phase active power filters for multiple nonlinear loads," *IEEE Trans. Power Electron.*, vol. 10, no. 3, pp. 263–272, May 1995.
- [18] D. N. Zmood, D. G. Holmes, and G. H. Bode, "Stationary frame current regulation of PWM inverters with zero steady-state error," *IEEE Trans. Power Electron.*, vol. 18, no. 3, pp. 814–822, Mar. 2003.
- [19] A. Timbus, M. Liserre, R. Teodorescu, P. Rodriguez, and F. Blaabjerg, "Evaluation of current controllers for distributed power

- generation systems,” *IEEE Trans. Power Electron.*, vol. 24, no. 3, pp. 654–664, Mar. 2009.
- [20] M. Castilla, J. Miret, J. Matas, L. G. de Vicuña, and J. M. Guerrero, “Linear current control scheme with series resonant harmonic compensator for single-phase grid-connected photovoltaic inverters,” *IEEE Trans. Ind. Electron.*, vol. 55, no. 7, pp. 2724–2733, Jul. 2008.
- [21] J. He and Y. W. Li, “Analysis, design and implementation of virtual impedance for power electronics interfaced distributed generation,” *IEEE Trans. Ind. Appl.*, vol. 47, no. 6, pp. 2525–2038, Nov./Dec. 2011.