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An Improved Current Control Scheme for Grid-Connected DG Unit Based Distribution System Harmonic Compensation

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***Abstract*—In order to utilize DG unit interfacing converters to actively compensate distribution system harmonics, this paper proposes an enhanced current control approach. It seamlessly integrates system harmonic mitigation capabilities with the primary DG power generation function. As the proposed current controller has two well decoupled control branches to independently control fundamental and harmonic DG currents, phase-locked loops (PLL) and system harmonic component extractions can be avoided during system harmonic compensation. Moreover, a closed-loop power control scheme is also employed to derive the fundamental current reference. The proposed power control scheme effectively eliminates the impacts of steady-state fundamental current tracking errors in the DG units. Thus, an accurate power control is realized even when the harmonic compensation functions are activated. Experimental results from a single-phase DG unit validate the correctness of the proposed methods.**

***Abstract*—active power filter, harmonic detection, phase-locked loop, and virtual impedance.**

I. INTRODUCTION

To address harmonic distortions caused by the increasing application of nonlinear loads, more active and passive filters shall be installed in the power distribution system. Alternatively, distribution system power quality enhancement using flexible operation of DG units has also been considered in [3-6, 8]. In the literature, the ancillary harmonic compensation capability is integrated with the DG primary power generation function by adding the local load harmonic current feedback to the DG unit current reference. Consequently, an accurate detection of load harmonic current is important. Various types of detection methods have been discussed before [3], such as the Fourier transformation based method in [9], the detection scheme using instantaneous real and reactive power theory in [10], and second-order generalized integrators in [11]. Alternatively, an interesting harmonic detection-less method was also proposed in [12, 13], where the main grid current is directly regulated instead of controlling DG current. However, it should be noted that direct regulation of grid side current often has stability concerns. To enhance the performance of DG units, developing a robust current control method without local load harmonic detection is very attractive.

On the other hand, the DG unit real and reactive power generation is indirectly regulated by the fundamental reference current tracking. The synchronized fundamental current reference can be determined based on the assumption of a stiff grid voltage. Nevertheless, this open-loop power control method may have some power control errors in a weak grid with PCC voltage variations. Moreover, for the DG unit with the ancillary harmonic compensation capability, interactions between DG harmonic currents and PCC harmonic voltages may further introduce some real and reactive power offsets. In order to realize accurate DG power generation, the aforementioned power control errors shall be compensated during DG current reference calculation. Therefore, a closed-loop power regulation method is needed for the DG unit.

Motivated by above discussions, this paper proposes a simple current controller with two parallel control branches. The first control branch is mainly responsible for DG unit power control, and the second one is employed to compensate either local load harmonic currents or PCC harmonic voltages. The references of these two control branches are directly derived from PCC voltage or local load current without any filtering. Therefore, conventional phase-locked loops or harmonic extractions in the active power filter systems are avoided. Moreover, by using the power control loop PI controller to regulate fundamental current reference, zero steady-state power tracking error can be realized. To verify the correctness of the proposed method, selective experimental results are provided in this paper.

II. DG UNITS WITH CONVENTIOANL CURRENT CONTROLLER

In this section, the principle of grid-connected DG unit with the active power filtering capability is briefly reviewed.

A. Local load harmonic current compensation

Fig. 1 illustrates the configuration of a single-phase DG system, where the DG interfacing converter is connected to PCC with a coupling choke (L_f and R_f). 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 is

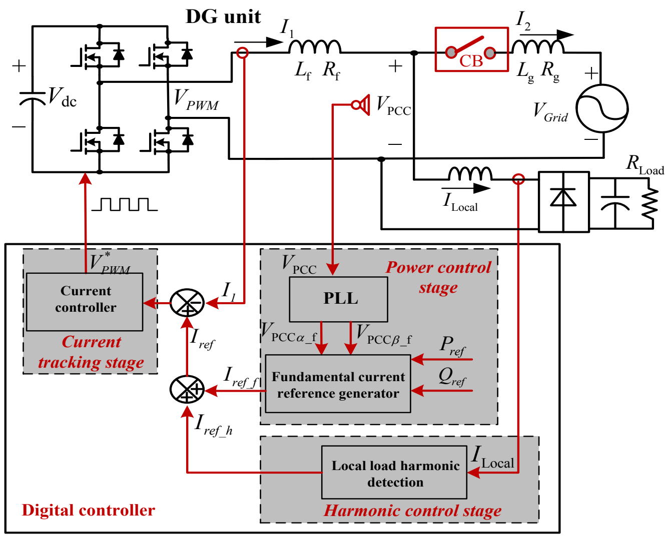

Fig.1. Diagram of a DG unit with local load harmonic current compensation.

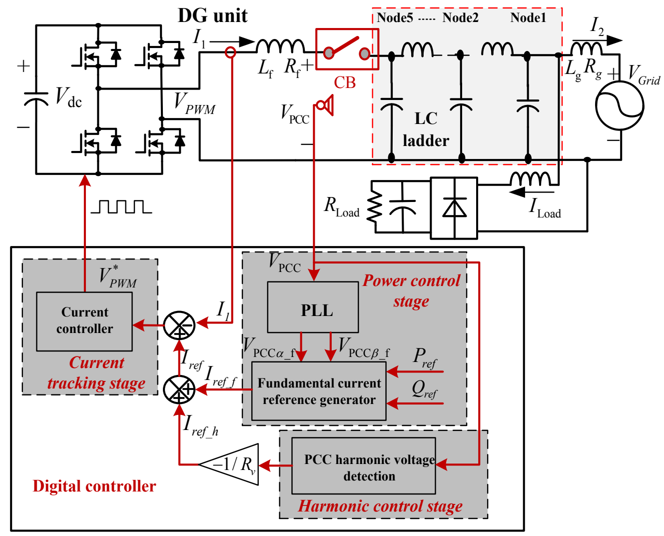

Fig.2. Diagram of DG unit with PCC harmonic voltage compensation.

composed of two parts. The first one is fundamental current reference (I_{ref_f}), which can be simply determined as

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

where P_{ref} and Q_{ref} are the real and reactive power reference, E^* is nominal RMS voltage magnitude of the DG system. The PCC voltage angle θ in (1) can be extracted by PLLs, such as the zero-crossing detection technique in [3].

The current reference generator in (1), however, is not accurate in controlling the injected power, due to the variations of PCC voltage magnitude. As a result, an improved power control method [6] with the consideration of PCC voltage fluctuations was developed as shown in (2)

$$I_{ref\_f} = I_{ref\alpha\_f} = \frac{(V_{PCC\alpha\_f}\cdot P_{ref} + V_{PCC\beta\_f}\cdot Q_{ref})}{V_{PCC\alpha\_f}^2 + V_{PCC\beta\_f}^2} \tag{2}$$

where$I_{ref_f}$is fundamental DG current reference, $I_{ref\alpha\_f}$ and $I_{ref\beta\_f}$ are the DG fundamental current reference and its orthogonal component in the artificial stationary $\alpha-\beta$ reference frame, and $V_{PCC\alpha\_f}$ and $V_{PCC\beta\_f}$ are PCC fundamental voltage and its orthogonal component in the $\alpha-\beta$ reference frame.

Moreover, to cancel the harmonic current of local nonlinear loads, the harmonic current reference I_{ref_h} shall also be derived by detecting the harmonic current component of local loads.

With derived fundamental and harmonic current references, the DG current reference is obtained as $I_{ref} = I_{ref\_f} + I_{ref\_h}$. Afterwards, the proportional and multiple resonant controllers [7] are adopted to ensure rapid current tracking as

$$\begin{aligned} V_{PWM}^* &= G_{cur}(s)\cdot(I_{ref} - I_1) \\ &= (K_p + \sum_{h=f,3,5,\ldots 15}\frac{2K_{ih}\omega_c s}{s^2 + 2\omega_c s + \omega_h^2})\cdot(I_{ref\_f} + I_{ref\_h} - I_1) \end{aligned} \tag{3}$$

where V_{PWM}^* is the reference voltage for PWM processing, $G_{cur}(s)$ is the current controller, K_P is the proportional gain, K_{ih} is the resonant controller gain at the order h, ω_c is the cut-off frequency of the controller, and ω_h is angular frequency at fundamental and selected harmonic frequencies.

B. PCC harmonic voltage compensation

It should be pointed out that the focus of local load compensation is to ensure sinusoidal grid current I_2 in Fig. 1. Indeed, the PCC harmonic voltage can be distorted especially when it is connected to the main grid with long underground cables, which are often modeled by an LC ladder [16]. To address LC ladder resonance issue, R-APF concept can be embedded in the DG unit current control as illustrated in Fig. 2. Compared to Fig.1, the DG harmonic current reference I_{ref_f} in this case is modified as

$$I_{ref\_h} = (-\frac{1}{R_V})\cdot(G_D(s)\cdot V_{PCC}) \tag{4}$$

where R_V is the virtual damping resistance at harmonic frequencies and $G_D(s)$ is the harmonic detector. With this modified harmonic current reference, DG unit works a harmonic damping resistor when it is viewed at power distribution system level.

III. PROPOSED HARMONIC COMPENSATION METHOD

Note that for either local load harmonic current compensation or PCC harmonic voltage compensation, the harmonic currents are absorbed by the DG unit. Consequently, interactions between DG harmonic current and PCC harmonic

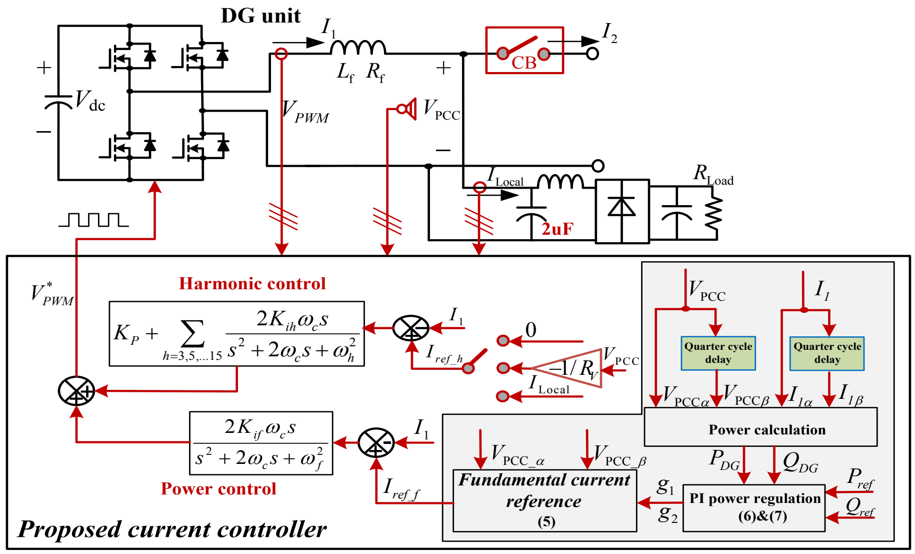

Fig. 3. Diagram of a DG unit with proposed control scheme.

voltage may cause steady-steady power offset. Nevertheless, the fundamental current reference in (2) is still derived in an open-loop manner, where only sinusoidal PCC fundamental voltages are considered in the calculation. Therefore, the power offset introduced by harmonic interactions can hardly be addressed in the conventional open-loop power control. Alternatively, it can be seen that closed-loop power control can effectively eliminate the power tracking errors. In this paper, a revised power control method is proposed to determine the fundamental current reference as

$$I_{ref\_f} = g_1 \cdot V_{PCC\alpha} + g_1 \cdot V_{PCC\beta} \tag{5}$$

where $V_{PCC\alpha}$ is the non-filtered PCC voltage expressed in the $\alpha-\beta$ reference frame ($V_{PCC\alpha} = V_{PCC}$) and $V_{PCC\beta}$ is its orthogonal signal. The gains g_1 and g_2 are adjustable and they are used to control DG unit real and reactive power, respectively. The detailed expression is given in (6) and (7) as

$$g_1 = (k_{p1} + \frac{k_{I1}}{s}) \cdot [\frac{1}{\tau s+1} \cdot (P_{ref} - P_{DG})] + \frac{P_{ref}}{(E^*)^2} \tag{6}$$

$$g_2 = (k_{p2} + \frac{k_{I2}}{s}) \cdot [\frac{1}{\tau s+1} \cdot (Q_{ref} - Q_{DG})] + \frac{Q_{ref}}{(E^*)^2} \tag{7}$$

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

$$P_{DG} = \frac{1}{2(\tau s+1)} \cdot (V_{PCC\alpha} \cdot I_{1\alpha} + V_{PCC\beta} \cdot I_{1\beta}) \tag{8}$$

$$Q_{DG} = \frac{1}{2(\tau s+1)} \cdot (V_{PCC\beta} \cdot I_{1\alpha} - V_{PCC\alpha} \cdot I_{1\beta}) \tag{9}$$

where $I_{1\alpha}$ is the non-filtered DG current expressed in stationary $\alpha-\beta$ frame ($I_1 = I_{1\alpha}$) and $I_{1\beta}$ is its delayed orthogonal component. Note that in (8) and (9), the steady-state power offset caused by harmonic voltage and harmonic current interactions is also addressed.

Although the proposed closed-loop power control method can eliminate power tracking errors, it can be seen that the fundamental current reference in (5) will have some ripples when the PCC voltage is distorted. When the DG current controller in (3) is used, the distorted fundamental current reference will inevitably affect the performance of harmonic current tracking. To overcome this drawback, an improved proportional and resonant controller with two control branches is proposed in this paper.

$$\begin{aligned} V^*_{PWM} = & \overbrace{\frac{2K_{if}\omega_c s}{s^2+2\omega_c s+\omega_f^2} \cdot (I_{ref\_f} - I_1)}^{Branch1:\ power\ control} \\ & \overbrace{+(K_P + \sum_{h=3,5,\ldots 15} \frac{2K_{ih}\omega_c s}{s^2+2\omega_c s+\omega_h^2}) \cdot (I_{ref\_h} - I_1)}^{Branch2:\ harmonic\ control} \\ & = \overbrace{G_f(s) \cdot (I_{ref\_f} - I_1)}^{Branch1:\ power\ control} + \overbrace{G_h(s) \cdot (I_{ref\_h} - I_1)}^{Branch2:\ harmonic\ control} \end{aligned} \tag{10}$$

As shown, the fundamental current reference derived from (5) is regulated by the "power control" branch. 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, this power control branch will not introduce any obvious harmonic disturbances to the harmonic control branch. Meanwhile, the harmonic current reference I_{ref_h} is regulated by the "harmonic control" branch, where only harmonic resonant controllers are included. As fundamental resonant controller is not used in the harmonic control branch, it is practical to remove the harmonic extractions in Figs. 1 and 2. Accordingly, the local

TABLE I. PARAMETERS IN EXPERIMENT

System Parameter	Value
Grid voltage	115V/50Hz
DG filter	L_f=6.5mH, R_f=0.15Ω
Grid feeder	L_g=3.4mH, R_g=0.15Ω
Sampling/Switching frequency	20kHz/10kHz
DC link voltage	350V
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 Kp	48
Resonant gains K_{ih}	1500(h=f); 900 (h=3, 5, 7, 9); 600 (h=11, 13, 15)
Resonant controller bandwidth ω_c	4.1rad/s

current or PCC voltage without filtering can be directly used as the input of the harmonic control branch. Note that when the harmonic current reference in (10) is zero, the harmonic control branch ensures that the DG current is ripple-free. This is very similar to the situation in the conventional DG unit control without compensating system harmonics, where the DG unit current is sinusoidal.

In summary, the harmonic current reference in (10) can have three options as given in (11)

$$I_{ref\_h} = \begin{cases} I_{Local} & \text{Local nonlinear load compensaion} \\ -V_{PoC} / R_V & \text{PoC harmonic voltage compensaion} \\ 0 & \text{DG harmonic current rejection} \end{cases} \quad (11)$$

With the proposed method in (10), another issue appears. Indeed, the proportional gain K_P in (10) will make the output of harmonic control branch has some fundamental contains. These fundamental contains may cause the interference with the power control branch. As a result, fundamental current tracking appears steady-state errors. Further considering that the fundamental current tracking in (10) essentially behaves as an inner loop of the closed-loop DG power (P_{DG} and Q_{DG}) regulation, the control scheme in (5), (6), and (7) still ensures zero steady-state power control error even when the fundamental current tracking has some errors.

The diagram of the proposed control method is shown in Fig. 3. It shows that the PLL and the harmonic detection process are removed from the DG controller.

IV. EXPERIMENTAL RESULT

The proposed method has been verified on the laboratory experimental prototype, where a single-phase grid-tied Danfoss inverter is the connected to a scaled down grid with 115V rated voltage magnitude. The real-time code for the experiment is generated by dSPACE 1005 and its peripheral FPGA (Field Programmable Gate Array).

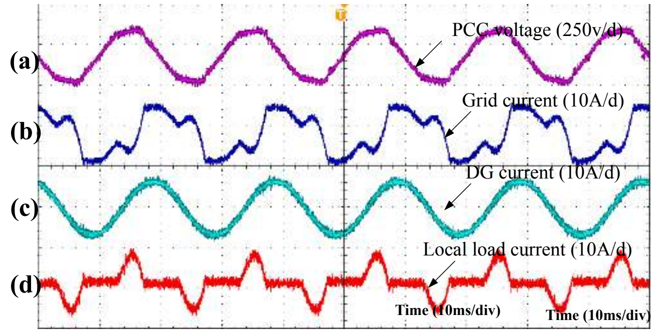

Fig. 4. Performance of a DG unit with nonlinear local loads. (DG current harmonic rejection)

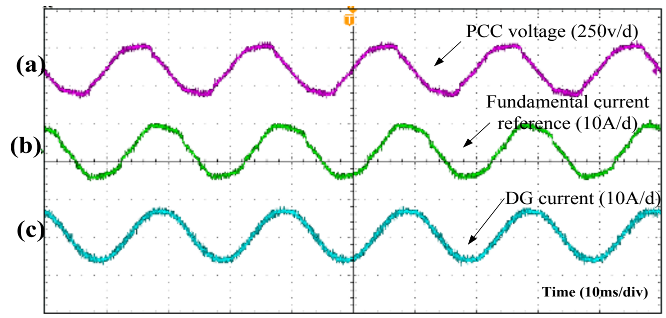

Fig. 5. Performance of a DG unit with nonlinear local loads. (DG current harmonic rejection)

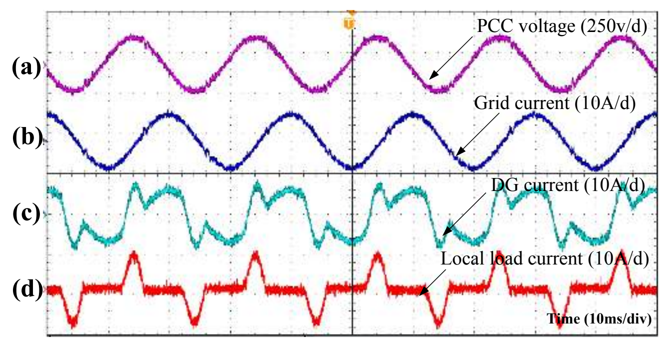

Fig. 6. Performance of a DG unit with nonlinear local loads. (Local load harmonic compensation)

First, the performance of the proposed method in addressing local load harmonic currents is tested. In order to filter out the switching ripple of the inverter, a small shunt capacitor (2uF) is also placed at PCC.

Fig. 4 shows the performance of the DG unit operating with $I_{ref\_h} = 0$ in (10). In this test, the DG real and reactive power references are 200W and 500Var. It can be seen that the DG current is sinusoidal and the local load harmonic currents flow to the main grid side. Accordingly, the THDs of DG and main grid currents are 5.16% and 41.73%, respectively. Meanwhile, due to the harmonic voltage drops on the grid feeder (L_g and R_g), the PCC voltage is also distorted with 9.49% THD.

The fundamental current reference corresponding to Fig. 4 is also provided in the middle trace of Fig. 5. As the fundamental current reference is related to non-filtered PCC voltage and its conjugated component, it is also distorted.

When the DG unit works at local harmonic compensation mode, the corresponding performance of the system is shown in Fig. 6. In this experiment, the measured local load current is directly employed as the input of the harmonic control branch ($I_{ref\_h} = I_{Local}$). It can be seen that the local load harmonic current are compensated by DG unit, resulted in an improved main grid current (with 3.64% THD). At the same time, the DG current is polluted with 51.08% THD.

The real and reactive power control performance under the local load harmonic compensation mode is also presented. To demonstrate the effectiveness of the proposed closed-loop power control method, the magnitude of main grid voltage is intentionally reduced to 107V. The performance using the proposed closed-loop power control method is shown in Fig. 7, where the real and reactive power reference changes from 100W/250Var to 200W/500Var. It can be seen that the proposed method always guarantees accurate power tracking even when the main grid voltage varies. The power control performance using the current reference generated in (1) is illustrated in Fig. 8 for comparison. In contrast to the performance using the proposed closed-loop power control, the variation of main grid voltage magnitude introduces nontrivial steady-state real and reactive power control errors.

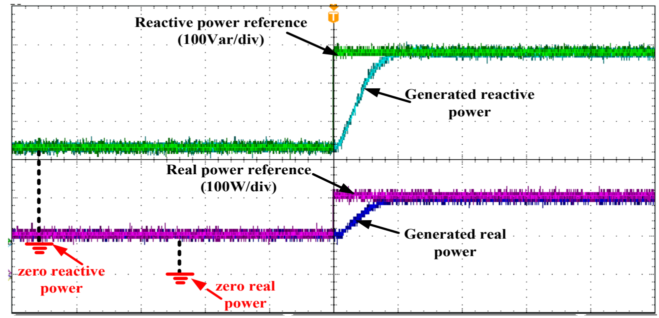

Fig. 7. Power control performance using the proposed closed-loop power control.

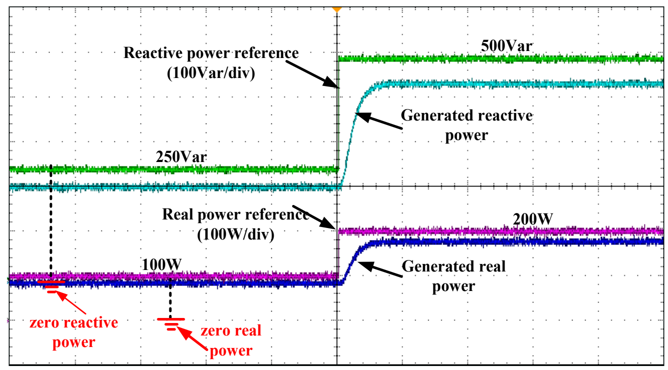

Fig. 8. Power control performance using conventional open-loop power control.

V. CONCLUSIONS

In this paper, a simple harmonic compensation strategy is embedded in the DG unit interfacing converters. By breaking the conventional proportional and multiple resonant controllers into two parallel control branches, the proposed method realizes distribution system harmonic compensation without using any phase-locked loops or system harmonic extractions. Moreover, the input of the fundamental power control branch is regulated by two PI controllers, which ensure an accurate power control even when the system harmonic compensation tasks are activated in the DG unit or the PCC voltage changes.

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