# Letters

# A Measurement Method to Solve a Problem of Using DG Interfacing Converters for Selective Load Harmonic Filtering

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***Abstract*—Flexible control of interfacing converter has been utilized to compensate the harmonics from nonlinear loads in a power distribution system. However, the site selection of a DG unit is mainly determined by the location of renewable energy resources that might be far away from the nonlinear load. This can degrade the performance of conventional nonlinear load current measurement methods using current transformers and shielded twisted-pair wires, and accordingly, make the harmonic compensation less effective. To solve this issue, the fundamental components of the PCC voltage and the DG installation point voltage are utilized to establish links between the DG unit controller and the power quality (PQ) meter for PCC nonlinear load monitoring. With this method, the harmonic current waveform can be accurately sent from the PQ meter to the DG unit controller with a very low bandwidth communication system, and it is not required to have any clock synchronization at the sending and the receiving ends of the communication system. Simulated and experimental results are provided to verify the correctness of the proposed measurement method.**

***Index Terms*—Active power filter, distributed generation, harmonic detection, power quality.**

## I. Introduction

DISTRIBUTED renewable energy resources have been increasingly interconnected to power distribution systems via power electronics interfacing converters [1]. As an interfacing converter often works at idle mode when the available power from the backstage system is lower than the rated power, using the ancillary service of interfacing converter to realize distribution system harmonic compensation has attracted a lot of interests from both the academia and the industry [2] and [3].

Previous research on harmonic compensation using multifunctional distributed generation (DG) units can be categorized into the following two areas:

1) avoid the conflicts between the harmonic compensation and the real power generation;
2) extend the current control bandwidth to achieve an accurate harmonic control.

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First, the adaptive harmonic compensation method is proposed in a few literatures [2] and [3], in which the measured load current is scheduled by an adaptive gain to get the harmonic current reference. The adaptive gain is determined according to the output power of the interfacing converter. With this method, the DG unit can avoid overloading problems when the harmonic compensation and the real power delivery are both activated in the interfacing converter system. Second, in order to realize a rapid response of the harmonic current mitigation, the wide bandwidth current controllers [4], such as deadbeat controller and hysteresis controller, are also adopted by the interfacing converter system.

It should be pointed out that before bringing the concept of multifunctional DG units into real engineering applications, a few existing problems must be solved. In this paper, an issue caused by the measurement of nonlinear load current is discussed. It is well known that a commercially available active power filter (APF) must be installed close to the nonlinear load or the service transformer of the distribution system, and accordingly, the analog current signals from the secondary of the current transformer (CT) for nonlinear load measurement can be connected to the APF controller with relatively short-shielded signaling wires. With this configuration, the electromagnetic interference (EMI) on harmonic current measurement system can be properly reduced. However, it is not the case for nonlinear load harmonic compensation using DG unit, as the DG installation site is not flexible and it is constrained by the geographic distribution of renewable energy resources. Accordingly, a DG unit can be far away from the nonlinear load. In this case, connecting the CT analog output to a DG unit controller for an accurate load current measurement is difficult. To the best of our knowledge, this field application issue has not been addressed in the literature, as the previous research was mainly conducted on compact laboratory prototypes.

To solve the aforementioned problem, a new current measurement method is proposed via the collaborative operation of a power quality (PQ) meter and a DG unit. This paper shows that the proposed method can effectively measure the load harmonic current by two steps. First, the nonlinear load harmonic current are extracted locally by a PQ meter and the harmonic signals are modulated with the fundamental component of point of common coupling (PCC) voltage signal. For the steady-state harmonics, the modulated signals are dc signals. Therefore, they can be sent to DG unit local controller with a low bandwidth communication system. Second, these dc signals are demodulated at DG unit local controller via the detection of DG installation point voltage.

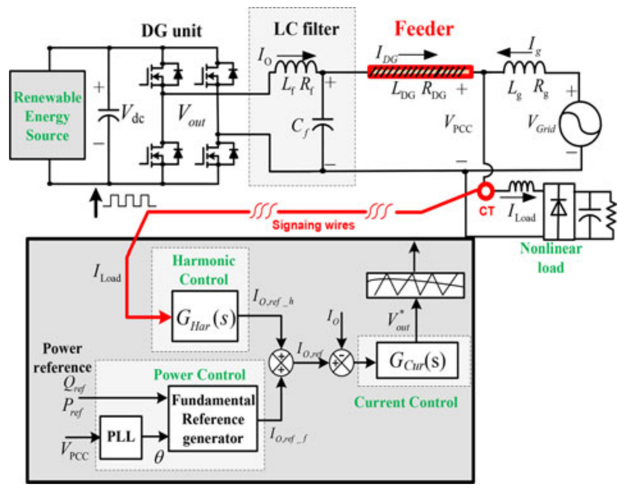


Fig. 1. Diagram of a DG unit that compensates the load harmonic current using conventional measurement method.

In this demodulation process, the impact of the difference between the DG installation point voltage and the PCC voltage is properly considered, in order to improve the harmonic current detection accuracy. It is important to emphasize that this proposed method does not require the expensive synchronized time clocks in the power meter and the DG unit controller. Therefore, it is very robust and the system is insensitive to the delay in the communication system.

## II. Proposed Measurement Method

### A. DG Operation Principle and Problem Definition

Fig. 1 shows the compensation of nonlinear load harmonics in a conventional way. The interfacing converter is coupled to an *LC* filter, and then the entire system is interconnected to PCC. When the harmonics from the load is cancelled by the DG unit, the grid current quality can be significantly improved at the steady state.

A DG controller with three subsystems is shown in the lower part of the figure. First, the fundamental current reference $I_{o,\mathrm{ref}\_f}$ is synchronized with the main grid by a phase-locked-loop and the current magnitude and the phase angle are derived according to the power reference $Q_{\mathrm{ref}}$ and $P_{\mathrm{ref}}$ [3]. Assuming that the instantaneous nonlinear load current is accurately measured by the DG unit local controller, a digital harmonic detector $G_{\mathrm{Har}}(s)$ in the DG unit controller is used to extract the harmonic components at selected harmonic frequencies. The extracted signal is adopted as the harmonic reference current $I_{\mathrm{o,ref}\_h}$. Once the harmonic component and the fundamental component of the reference current are known, the reference current $I_{o,\mathrm{ref}}$ can be obtained and a current controller $G_{\mathrm{Cur}}(s)$ with wide control bandwidth shall be used to ensure a rapid current tracking. Note that the selective harmonic compensation is considered as a way to more efficiently compensate the most dominate system harmonics, as discussed in [11] and [12]. In addition, when the DG unit is connected to PCC with a long feeder, compensating very high frequency harmonics may adversely cause interference with nearby communication systems. Due to the above considerations, the selective harmonic compensation algorithm is adopted in this paper.

It is important to emphasize that the selection of DG unit installation site is constrained by the location of renewable energy resources that are often far away from the nonlinear loads at PCC. When the aforementioned measurement method is adopted, the distance from the secondary of CTs to the DG unit controller can be out of the wire length limitations for conventional APF application. In this case, using a conventional method to accurately measure PCC load harmonic current is difficult.

### B. Problem-Solving Methodology

A new harmonic current measurement method through the coordinated operation of a DG unit controller and a PQ meter is proposed in this section.

*1) Harmonic Detection by PQ Meter:* The PQ meter is increasingly installed to monitor the comprehensive power distribution system power quality issues, such as harmonics, interharmonics, and rapidly change voltages [10]. It can also be utilized for nonlinear load harmonic current detection. Specifically, a PQ meter can dynamically monitor the harmonics of the load current at selected harmonic orders by obtaining the corresponding magnitude and phase angle. First, a PQ meter is installed closed to the nonlinear load. The fundamental frequency component of PCC voltage $V_{\mathrm{PCC}}$ and the harmonic components of load current $I_{\mathrm{Load}}$ are extracted using a sliding discrete Fourier transform (DFT) (SDFT) at the PQ meter as

$$\begin{aligned}\vec{I}_{\mathrm{Load},h} &= M_{\mathrm{Load},h}(t_1)\cdot\angle\theta_{\mathrm{Load},h}(t_1)\\ &= H_{\mathrm{SDFT},h}(s)\cdot I_{\mathrm{Load}}\end{aligned} \tag{1}$$

$$\begin{aligned}\vec{V}_{\mathrm{PCC},f} &= M_{\mathrm{PCC},f}(t_1)\cdot\angle\theta_{\mathrm{PCC},f}(t_1)\\ &= H_{\mathrm{SDFT},f}(s)\cdot V_{\mathrm{PCC}}\end{aligned} \tag{2}$$

where $H_{\mathrm{SDFT},h}(s)$ is the transfer function of the SDFT and *h* is the harmonic order, $M_{\mathrm{PCC},f}\ (t_1)$ and $M_{\mathrm{Load},h}\ (t_1)$ are the PCC voltage magnitude and the load harmonic current magnitude at the order *h*, respectively. $\theta_{\mathrm{PCC},f}\ (t_1)$ and $\theta_{\mathrm{Load},h}(t_1)$ are the PCC voltage phase angle and the load harmonic current phase angle at the order *h*, respectively. $t_1$ is the time clock of the PQ meter.

For a steady-state nonlinear load, the angle of load harmonic current component at the order *h* and the angle of fundamental frequency PCC voltage has the following relationship, where $d_h(t_1)$ is a dc value:

$$\angle\theta_{\mathrm{Load},h}(t_1) - h\cdot\angle\theta_{\mathrm{PCC},f}(t_1) = d_h(t_1). \tag{3}$$

*2) Receiving of Harmonic Component Signal in DG Controller:* If the angle $[\theta_{\mathrm{PCC},f}\ (t_1)]$ of fundamental frequency PCC voltage can be known by the DG unit local controller, the steady-state load harmonic current at the specific order *h* can be accurately retrieved by the DG unit local controller via receiving angle difference $d_h(t_1)$and the magnitude $M_{\mathrm{Load},h}(t_1)$. Note that they are dc signals, therefore, they can be easily sent from a power meter to a DG unit with a low sampling rate communication system [5]–[7].

The receiving of the harmonic current signals at the DG unit local controller is demonstrated here. First, if the feeder impedance between the DG unit and the PCC is small, it is practical to assume that PCC voltage angle equals to the angle of capacitor voltage of the interfacing converter *LC* filter. In this case, the angle of capacitor voltage is detected by the DG unit local controller and a demodulator can be used to get the load harmonic current signals.

However, when a DG unit is installed far away from PCC, the voltage drop on the feeder impedance cannot be ignored. To compensate the impact of this voltage drop, a new detection method is proposed here. Note that the accuracy of feeder impedance estimation is important for the implementation of the proposed method. Thanks to the newly developed schemes for feeder impedance estimation, the DG unit feeder impedance can be accurately detected as shown in [8] and [9]. Thus, it is reasonable to assume that the feeder impedance $L_{\rm DG}$ and $R_{\rm DG}$ is known before the implementation of the proposed method.

At the DG unit local controller, the capacitor voltage and the DG unit output current are measured and their fundamental frequency components are extracted as

$$\vec{I}_{o,f} = M_{I_O,f}(t_2) \cdot \angle\theta_{Io,f}(t_2) = H_{\rm SDFT,f}(s) \cdot I_o \quad (4)$$

$$\overrightarrow{V}_{CV,f} = M_{C,f}(t_2) \cdot \angle\theta_{C,f}(t_2) = H_{\rm SDFT,f}(s) \cdot V_C \quad (5)$$

where $M_{Io,f}(t_2)$ and $M_{C,f}(t_2)$are the magnitude *o* fundamental frequency component of DG output current and filter capacitor voltage, respectively. $\theta_{Io,h}(t2)$ and $\theta_{C,f}\ (t2)$ are their corresponding phase angles. $t2$ is the time clock of the DG unit controller. Based on a simple relationship

$$\begin{cases} \vec{V}_{C,f} - (R_{\rm DG} + jX_{\rm DG})\vec{I}_{{\rm DG},f} = \vec{V}_{{\rm PCC},f} \\ \vec{I}_{O,f} - \vec{I}_{C,f} = \vec{I}_{{\rm DG},f} \\ \vec{I}_{C,f} = j\omega_o C_f \cdot \vec{V}_{C,f} \end{cases} \quad (6)$$

where the PCC voltage angle can be easily identified by the DG controller as

$$\angle\theta^*_{\rm PCC}(t2) = {\rm atan}\left(\frac{R_{\rm DG}\cdot A - X_{\rm DG}\cdot B}{X_{\rm DG}\cdot A + R_{\rm DG}\cdot B}\right) \quad (7)$$

where $X_{\rm DG} = j\omega_o L_{\rm DG}$ and $R_{\rm DG}$ are the feeder reactance and resistance, respectively. $\omega_o$ is the angular fundament frequency,$I_{{\rm DG},f}$ is the DG fundamental frequency current, $I_{c,f}$ is the capacitor fundamental frequency current, and the coefficients A and B in (7) are expressed as

$$A = M_{Io,f}\cos(\theta_{Io,f}(t_2)) + \omega_0 C_f M_{Vc,f}\sin(\theta_{Vc,f}(t_2)) \quad (8)$$

$$B = M_{Io,f}\sin(\theta_{Io,f}(t_2)) - \omega_0 C_f M_{Vc,f}\cos(\theta_{Vc,f}(t_2)). \quad (9)$$

It is important to note that the time clocks of the PQ meter and the DG unit controller are not necessarily to be synchronized. As a result, $t_1$ of the PQ meter is not equal to $t_2$ of the DG unit local controller, but the following relationship is valid at any time instant:

$$\angle\theta^*_{{\rm PCC},f}(t_2) = \angle\theta_{{\rm PCC},f}(t_1) \quad (10)$$

$$M^*_{{\rm Load},h}(t_2) = M_{{\rm Load},h}(t_1). \quad (11)$$

Accordingly, the harmonic signals from the PQ meter can be retrieved in the DG unit controller as

$$\angle\theta^*_{{\rm Load},h}(t_2) = \angle d_h(t_2) + h\cdot\angle\theta^*_{{\rm PCC},h}(t_2) \quad (12)$$

$$M^*_{{\rm Load},h}(t_2) = M_{{\rm Load},h}(t_1). \quad (13)$$

When the load harmonic current magnitude and angle are obtained, the instantaneous load harmonic current $I_{{\rm Load},h}$ is determined as

$$I_{{\rm Load},h} = \sum_{h=3,5,7,9,11,13} M^*_{{\rm Load},h}(t_2)\cdot\cos(\theta^*_{{\rm Load},h}(t_2)). \quad (14)$$

*3) DG Unit Current Tracking:* When the detected load harmonic current in (14) is used as the reference current harmonic component, a proportional and resonant (P+R) current regulator is used for selective harmonic compensation as

$$\begin{aligned} V_{\rm out,ref} &= G_{\rm Cur}(s)\cdot(I_{o,\rm ref} - I_o) \\ &= \left(k_p + \sum_{h=1,3,\ldots 13}\frac{2k_{i,h}\omega_c s}{s^2 + 2\omega_c s + (h\cdot\omega_o)^2}\right) \\ &\quad \cdot(I_{o,{\rm Load}\_h} + I_{o,{\rm ref}\_f} - I_o) \end{aligned} \quad (15)$$

where $k_p$ is the proportional gain, $k_{i,h}$ is the resonant controller gain at the order *h*, and $\omega_{\rm c}$ is the cutoff frequency of the resonant controller.

## III. Verification Results

The effectiveness of the proposed measurement method has been verified by simulated and experimental results. The configuration of the system is the same as that in Fig. 2. The detailed parameters for the simulated and experimental system can be seen in Table I.

First, a simulation model is established and the detected harmonic signals in the PQ meter are sent to a DG unit controller via a low bandwidth communication system with 100-Hz sampling frequency and a 10 ms fixed-time delay is added to the sampled system.

When the instantaneous harmonic current waveforms in PQ meter are directly sent to the DG unit controller without using any modulations, the performance is shown in Fig. 3. It is obvious that the very low bandwidth communication is incapable of sending the harmonic signals correctly to the DG unit controller. As a result, the grid current is highly distorted even after the compensation.

When assuming that the voltages of the filter capacitor and the PCC have the same phase angle, the performance of the system is shown in Fig. 4. In this case, although the grid current is improved compared to the counterpart in Fig. 3, there are some distortions as the demodulated harmonic load signals in the DG unit are not exactly the same as the original harmonic signals in the PQ meter.

In the last simulation, the angle difference between the PCC and the filter capacitor voltage is properly considered by the proposed estimator in (7). The performance of the system is shown in Fig. 5. It can be clearly seen that the received signals

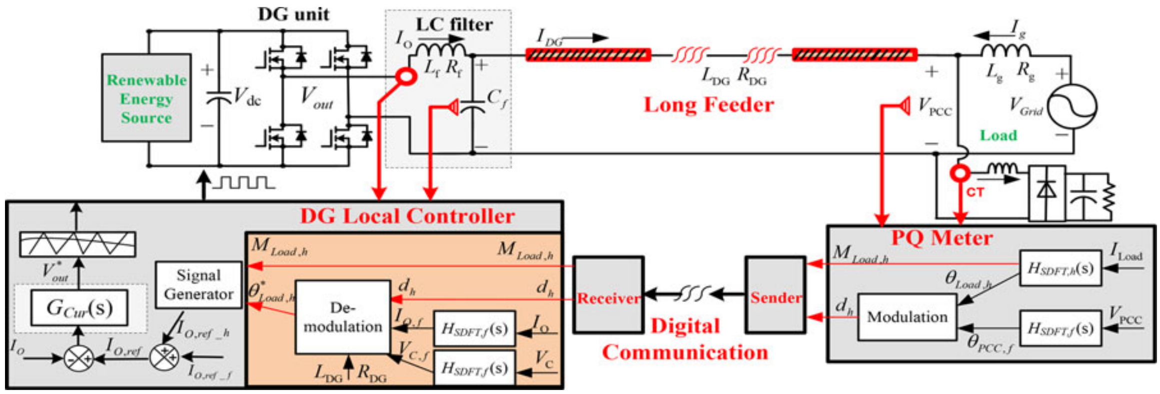


Fig. 2. DG unit to compensate load harmonic current using the proposed measurement method.

TABLE I
PARAMETERS OF THE SIMULATED AND EXPERIMENTAL SYSTEM

| Circuit Parameter | Value |
|---|---|
| Rated grid voltage | 120 V per phase |
| Sampling and Switching Frequency | 20 kHz/10 kHZ |
| *LC* filter | 0.8 mH 8.7 uF |
| Feeder Impedance | 2.5 mH 2.5 Ω |
| Dead-time | 2.2 $\mu$s |
| Communication System Sampling Frequency | 100 Hz |
| **Control parameter** | **Value** |
| Current Control Loop | $k_p = 1.3$<br>$k_{i,h} =$<br>2550, $h = 1$;<br>1200, $h = 3, 5, 7, 9$;<br>1000, $h = 11.13$ |

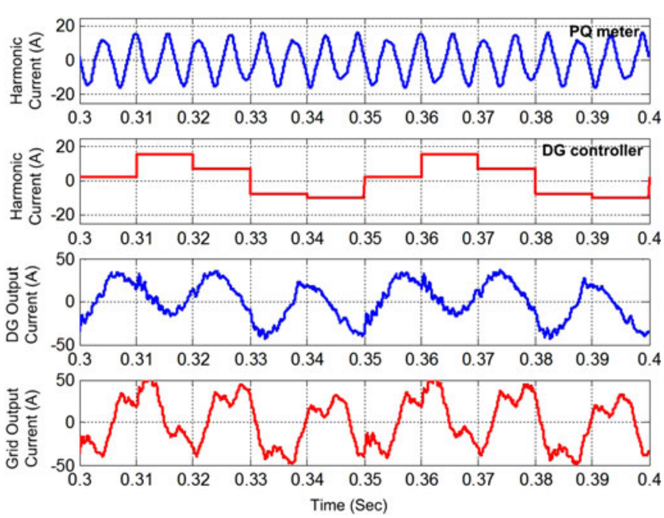


Fig. 3. PQ meter harmonic current signal is directly sent to DG controller with a zero-order hold with 100 Hz sampling frequency (upper to lower: harmonic current measured by PQ meter, harmonic current signal received by DG controller, DG output current, main grid current).

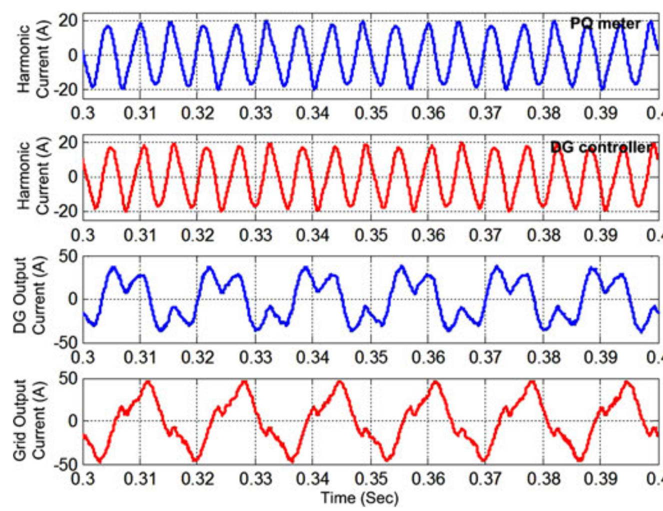


Fig. 4. PQ meter harmonic current signal is sent to DG controller via the proposed method but without considering feeder voltage drop (upper to lower: harmonic current measured by PQ meter, harmonic current signal received by DG controller, DG output current, main grid current).

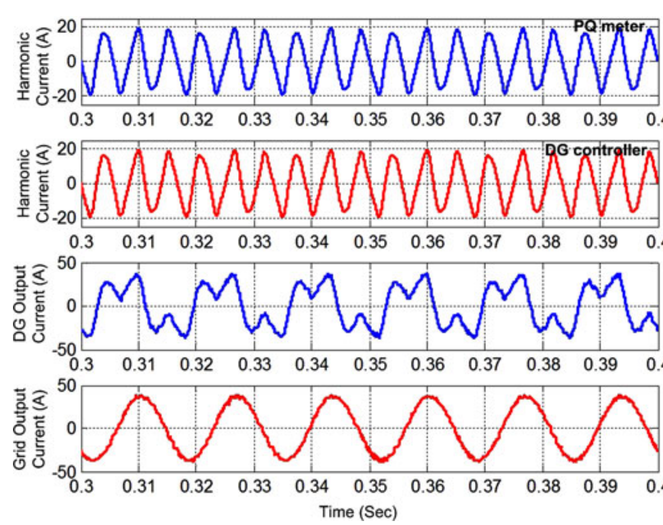


Fig. 5. PQ meter harmonic current signal is sent to DG controller via the proposed method (upper to lower: harmonic current measured by PQ meter, harmonic current signal received by DG controller, DG output current, main grid current).

in the DG unit local controller are almost the same as that in the PQ meter. Accordingly, the grid current quality is significantly improved as the DG output current has an excellent tracking of the reference.

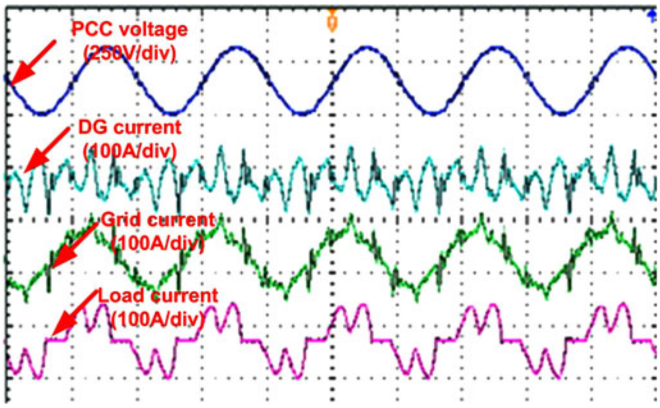


Fig. 6. Performance of the experimental system using the proposed measurement method but without considering feeder voltage drop.

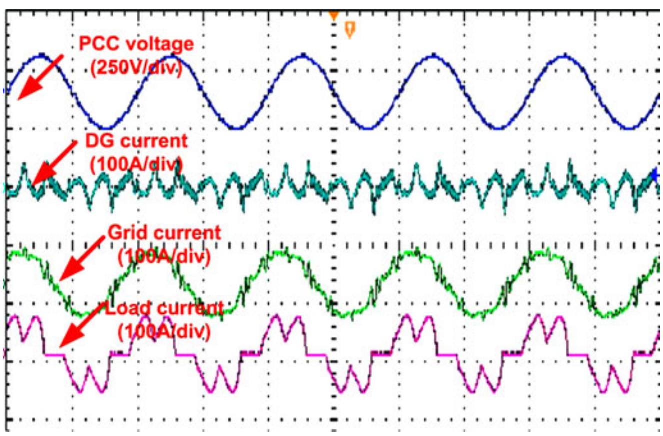


Fig. 7. Performance of the experimental system using the proposed measurement method by compensating the impact of feeder impedance drop.

The performance of the system is also verified on an experimental test rig. A PQ meter is used to extract the harmonics and a laboratory-made communication board is used to send the modulated harmonic signals to a TMLSF28335-based DG unit controller via RS485 protocol, which, in theory, allows the length of the communication wire up to 1219 m for 10 Mb/s broadband.

The performances of the system under various situations are shown in Figs. 6 and 7, where it can be seen that the load current is highly distorted with 32.91% THD. First, when the proposed measurement method is applied to the system but the feeder voltage drop is not considered, the performance is shown in Fig. 6. In this test, the grid current is improved and the THD is 11.12%. By properly compensating the impact of the angle difference between PCC voltage and DG voltage, the load harmonic current is properly compensated and the grid current as shown in Fig. 7 is further improved with 6.27% THD.

## IV. Conclusion

This paper discusses a problem of using DG units for power distribution system power quality enhancement. To solve this problem, a digitally current measurement method is proposed by using a low bandwidth communication between the PQ meter and the DG unit controller. The characteristics and merits of the proposed method are summarized here:

1) Increase the limit of distance between the DG unit and PCC loads. Therefore, even remotely installed DG unit can be used to compensate PCC load harmonics.
2) Harmonic signals are sent by a digitally low bandwidth communication system that can effectively mitigate EMI caused by long CT wires.
3) The time clocks of the sender in the PQ meter and the receiver in the DG controller are not required to be synchronized. Thus, the cost of the communication system can be significantly reduced.

It is important to note that the voltage measurement is used as a link for the PQ meter and the DG controller. Other public information of the system can also be used to realize this communication and it will be reported shortly in our future research work.

## 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] 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.

[3] R. Bojoi, L.R. Limongi, D. Roiu, 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.

[4] A. Timbus, M. Liserre, R. Teodorescu, P. Rodrigue, 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.

[5] V. C. Gungor, D. Sahin, T. Kocak, S. Ergut, C. Buccella, C. Cecati, and G. P. Hancke, "Smart grid technologies: Communication technologies and standards," *IEEE Trans. Ind. Inf.*, vol. 7, no. 4, pp. 529–539, Jul. 2011.

[6] J. M. Guerrero, J. C. Vasquez, J. Matas, L. G. de Vicuna, and M. Castilla, "Hierarchical control of droop-controlled AC and DC microgrids—A general approach toward standardization," *IEEE Trans. Ind. Electron.*, vol. 55, no. 1, pp. 158 - 172, Jan. 2011.

[7] J. He, Y. W. Li, J. Guerrero, F. Blaabjerg, and J. Vasquez, "An Islanding microgrid power sharing approach using enhanced virtual impedance control scheme," *IEEE Trans. Power Electron.*, vol. 28, no. 11, pp. 5272–5282, Nov. 2013.

[8] L. Asiminoaei, R. Teodorescu, F. Blaabjerg, and U. Borup, "A digital controlled PV-inverter with grid impedance estimation for ENS detection," *IEEE Trans. Power Electron.*, vol. 20, no. 6, pp. 1480–1490, Jun. 2005.

[9] S. Sanchez and M. Molinas "Large signal stability analysis at the common coupling point of a DC microgrid: A grid impedance estimation approach based on a recursive method", *IEEE Trans. Energy Convers.*, vol. 30, no. 1, pp. 122–131, Mar. 2015.

[10] D. Della Giustina, P. Ferrari, A. Flammini, and S. Rinaldi, "Synchronization requirements of a power quality measurement system for the distribution grid," in *Proc. IEEE Int. Instrum. Meas. Technol. Conf.*, 2014, pp. 245–250.

[11] C. Lascu, L. Asiminoaei, I. Boldea, and F. Blaabjerg, "High performance current contreoller for selective harmonic compensation in active power filters," *IEEE Trans. Power Electron.*, vol. 22, no. 5, pp. 1826–1835, May. 2007.

[12] G. Escobar, P. Mattavelli, A.M. Stankovic, A.A. Valdez, and J. Leyva-Ramos, "An adaptive control for UPS to compensate unbalance and harmonic distortion using a combined capacitor/load current sensing," *IEEE Trans. Ind. Electron.*, vol. 54, no. 2, pp. 158–839–158-847, Feb. 2007.