Design and Implementation of a Single-Phase Shunt Active Power Filter Based on PQ Theory for Current Harmonic Compensation in Electric Distribution Networks

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***Abstract*— This paper proposes the design and implementation of a single-phase shunt active power filter based on the PQ theory to compensate current harmonics in electric distribution networks. The proposed method precisely extracts current harmonics by using the second order generalized integrator. Also, a simple current controller tracks the converter reference current resulting in a highly sinusoidal grid current in-phase with the grid voltage. Simulation and experimental results on a typical household load confirm the correct and appropriate performance of the proposed system.**

Keywords—PQ theory; single-phase active power filter; second order generalized integrator; electric distribution network.

I. Introduction

Nowadays, nonlinear loads such as variable speed drives, switch-mode power supplies, CFL and LED light bulbs, welding inverters and so on are vastly utilized in electric distribution networks. These loads draw non-sinusoidal currents from utility grid even with sinusoidal voltages. Current harmonics in distribution networks cause several problems, the main being increased neutral current in four-wire systems, overload and over temperature of system components, extra losses, mechanical oscillations in motors, insulation failures, unpredictable behavior of protection systems, interference with communication systems, etc.

Passive and active filters are used to mitigate current harmonics in electric distribution networks. Passive filters are constructed by a proper arrangement of inductors and capacitors. Despite the simplicity, these filters suffer from disadvantages of large volume, high cost and especially the susceptibility to resonances. In addition, these filters should be installed with a large capacity to compensate acceptable level of harmonics. Shunt active power filters (APFs), shown in Fig. 1, attract more tendency than other harmonic compensation techniques, due to the fast response and the extra flexibility they offer. These filters have the capability to selectively compensate the desired harmonics and the reactive component in an effective way. Active power filters are composed of power semiconductor switches, inductors and capacitors. The performance of active power filters depends on the quality of the harmonic current identification and the power electronic converter control methods. Up to now, many different methods are suggested [1]-[6].

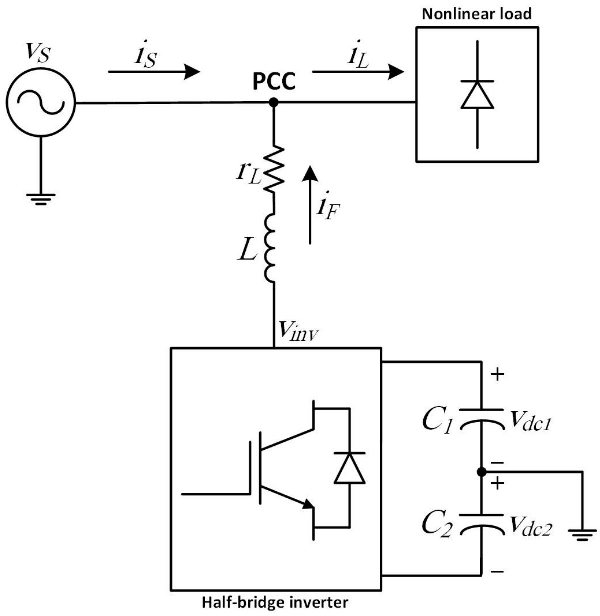

Fig. 1. Single-phase shunt active power filter.

This paper proposes the design and implementation of a single-phase shunt active power filter for current harmonic compensation in electric distribution networks. A PQ second-order generalized integrator (SOGI) based control technique is presented in this paper, which can generate an in-phase pure sinusoidal current with the non-ideal grid voltage. Also, due to simplicity and less number of power switches, a single-phase half-bridge converter is used to inject current harmonics to the grid. In the following, the control algorithm and the design procedure are described in details.

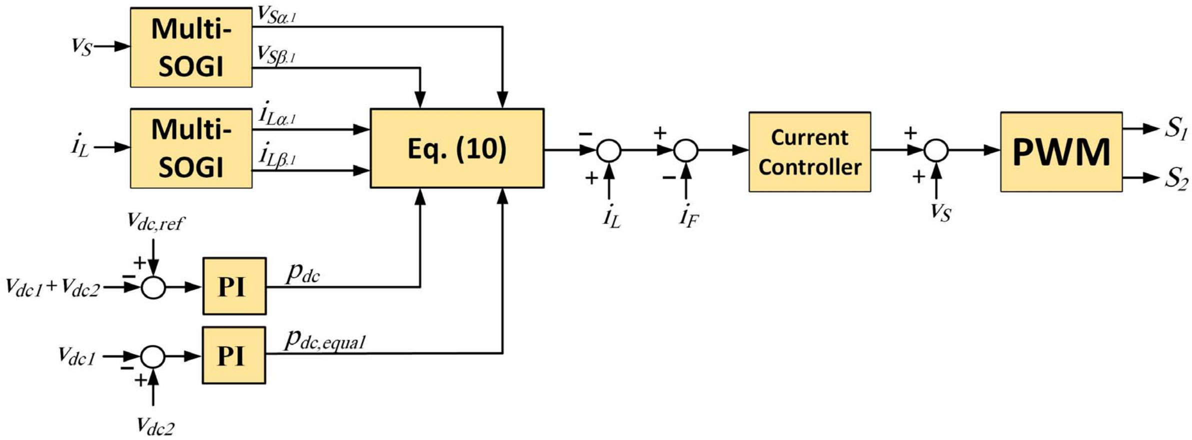

Fig. 2. Block diagram of single-phase shunt active power filter.

II. Proposed Control Algorithm

A. Signple-phase PQ Theory

The instantaneous active and reactive power theory, which is also called the PQ theory was first introduced for three-phase systems by Akagi *et al.* [2]. However the single-phase version is also successfully developed in [5]-[6], but in some references, it is assumed that the source voltage has a pure sinusoidal waveform, which can lead to performance degradation of the control algorithm in practice. The single-phase PQ theory uses the source voltage and the load current as the α-axis quantities and their 90° phase-shifted versions as the fictitious β-axis quantities. Therefore, the system is represented as a pseudo two-phase system. If we assume that the source voltage has a pure sinusoidal waveform, then its representation in the αβ coordinates is

$$\begin{bmatrix} v_{S\alpha}(\omega t) \\ v_{S\beta}(\omega t) \end{bmatrix} = \begin{bmatrix} v_S(\omega t + \varphi_V) \\ v_S(\omega t + \varphi_V + \frac{\pi}{2}) \end{bmatrix} = \begin{bmatrix} V_m \sin(\omega t + \varphi_V) \\ V_m \cos(\omega t + \varphi_V) \end{bmatrix} \quad (1)$$

Also, the load current representation in the αβ coordinates is

$$\begin{bmatrix} i_{L\alpha}(\omega t) \\ i_{L\beta}(\omega t) \end{bmatrix} = \begin{bmatrix} i_L(\omega t + \varphi_I) \\ i_L(\omega t + \varphi_I + \frac{\pi}{2}) \end{bmatrix} \quad (2)$$

where V_m, ω, φ_V and φ_I are the source voltage amplitude, source frequency, source voltage phase and load current phase, respectively. Then, the single-phase instantaneous active and reactive powers in the αβ coordinates are defined as

$$\begin{bmatrix} p \\ q \end{bmatrix} = \begin{bmatrix} v_{S\alpha} & v_{S\beta} \\ -v_{S\beta} & v_{S\alpha} \end{bmatrix} \begin{bmatrix} i_{L\alpha} \\ i_{L\beta} \end{bmatrix} \quad (3)$$

The instantaneous active and reactive powers can be represented as

$$p = \bar{p} + \tilde{p} \quad (4)$$

$$q = \bar{q} + \tilde{q} \quad (5)$$

where the DC components, $\bar{p}$ and $\bar{q}$, express the fundamental active and reactive powers, while the AC components, $\tilde{p}$ and $\tilde{q}$, express the oscillating active and reactive powers, respectively. The fundamental active component of the load current can be then easily calculated from (3) as [3]

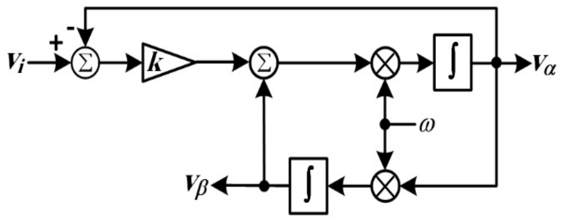

Fig. 3. Second order generalized integrator (SOGI) [7].

$$\begin{aligned} \begin{bmatrix} i_{L\alpha,p} \\ i_{L\beta,p} \end{bmatrix} &= \begin{bmatrix} v_{S\alpha,1} & v_{S\beta,1} \\ -v_{S\beta,1} & v_{S\alpha,1} \end{bmatrix}^{-1} \begin{bmatrix} \bar{p} \\ 0 \end{bmatrix} \\ &= \frac{1}{v_{S\alpha,1}^2 + v_{S\beta,1}^2} \begin{bmatrix} v_{S\alpha,1} & -v_{S\beta,1} \\ v_{S\beta,1} & v_{S\alpha,1} \end{bmatrix}^{-1} \begin{bmatrix} \bar{p} \\ 0 \end{bmatrix} \end{aligned} \quad (6)$$

Since, it is desired that only the fundamental active component of the load current is drawn from the source, then the reference source current is simply derived from (6), as

$$i_{S,ref} = i_{L\alpha,p} = \frac{v_{S\alpha,1}}{v_{S\alpha,1}^2 + v_{S\beta,1}^2} \times \bar{p} \quad (7)$$

where $\bar{p}$ can be extracted from p by a low-pass filter (LPF) or directly calculated from the fundamental components of the currents and voltages. Also, to keep the DC-link voltage constant, an active power p_{dc}, which compensates the APF power losses, is added to (7) as

$$i_{S,ref} = i_{L\alpha,p} = \frac{v_{S\alpha,1}}{v_{S\alpha,1}^2 + v_{S\beta,1}^2} \times (\bar{p} + p_{dc}) \quad (8)$$

Also, it is clear from Fig. 1 that a half-bridge inverter is used, then a term $p_{dc,equal}$ is introduced to equalize the voltages of upper and lower DC-link capacitors, resulting in (9).

$$i_{S,ref} = i_{L\alpha,p} = \frac{v_{S\alpha,1}}{v_{S\alpha,1}^2 + v_{S\beta,1}^2} \times (\bar{p} + p_{dc}) - p_{dc,equal} \quad (9)$$

So, the final reference source current is

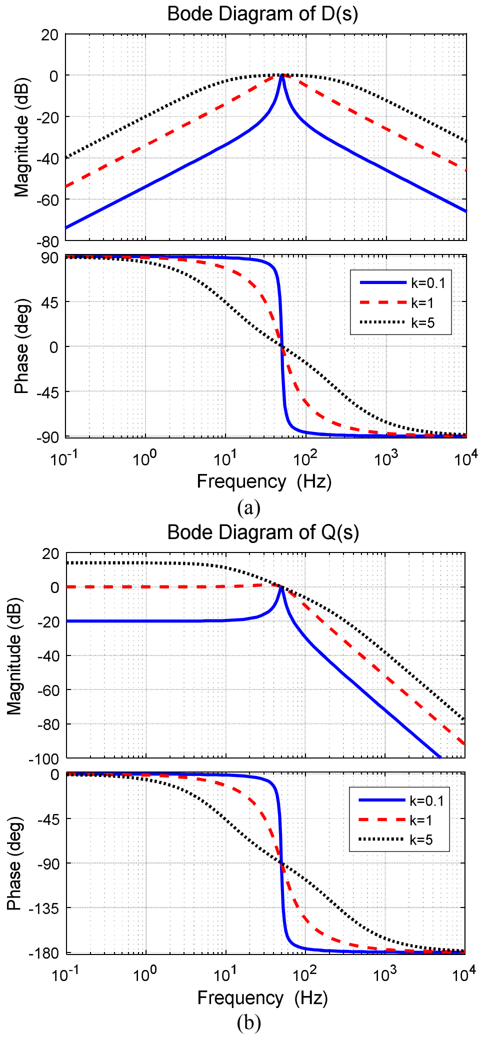

Fig. 4. Bode diagrams of SOGI transfer functions for different values of k: (a) $D(s)$, and (b) $Q(s)$.

$$i_{S,ref} = \frac{\left(v_{S\alpha,1} i_{L\alpha,1} + v_{S\beta,1} i_{L\beta,1} + p_{dc}\right) v_{S\alpha,1}}{v_{S\alpha,1}^2 + v_{S\beta,1}^2} - p_{dc,equal} \quad (10)$$

As can be seen in (7) to (10), the source voltage has a main role in the reference current generation of the single-phase APF. The presence of any distortions in the voltages in (10) directly translates to distortions in the grid reference current.

B. Second Order Genralized Integrator Based PQ Theory

The second order generalized integrator (SOGI) is used to generate the filtered αβ-axis quantities from the source voltage and the load current. Fig. 2 shows the suggested control block diagram of the single-phase APF. The SOGI structure is shown in Fig. 3 [7]-[8]. This structure is composed of two integrators and a damping factor k. This factor has an important role in the filtering and dynamic performance; such that a small value for k results in a high level of filtering, but the settling time of the β-axis output will be too long. The characteristic transfer functions of the SOGI are [7]-[8]

$$D(s) = \frac{v_{S\alpha}(s)}{v_S(s)} = \frac{k\,\omega s}{s^2 + k\,\omega s + \omega^2} \quad (11)$$

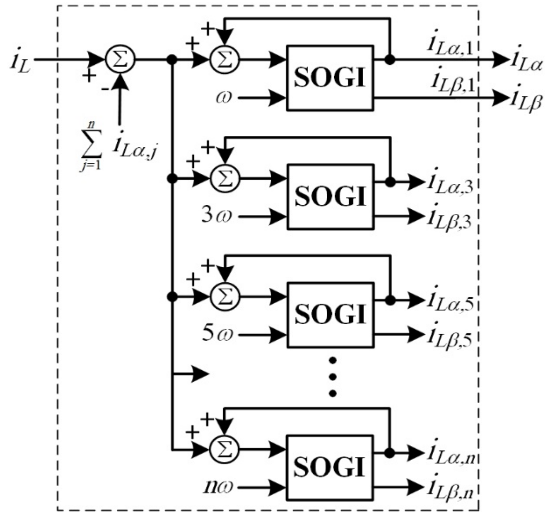

Fig. 5. Multi-SOGI.

$$Q(s) = \frac{v_{S\beta}(s)}{v_S(s)} = \frac{k\,\omega^2}{s^2 + k\,\omega s + \omega^2} \quad (12)$$

Figs. 4(a) and (b) show the Bode diagrams of the transfer functions $D(s)$ and $Q(s)$, respectively, for different values of k. It is observed from these figures that decreasing the value of k results in narrower bandwidth. By applying the inverse Laplace transform to (11) and (12), the settling time for the extraction of the α and β components can be approximated as [3]

$$t_s \cong \frac{8}{k\,\omega} \quad (13)$$

Therefore, by considering a value for settling time t_s, the damping factor k can be easily determined. But, when a high distorted load is connected to the grid, the performance of the fundamental current extraction despite of the low value of k is not even satisfactory. To solve this problem, one can add extra SOGI blocks in parallel with the main SOGI block, which is tuned at the fundamental frequency, called the multi-SOGI structure. Each of added SOGI blocks is tuned at the desired harmonic frequency to attenuate this harmonic component in the output of the multi-SOGI structure. Therefore the extraction of the fundamental component of the load current can be improved by selectively mitigating the desired low-order harmonic components. Fig. 5 shows the multi-SOGI structure. In this paper, due to the non-ideality of the grid voltage and highly distorted load currents, two SOGI blocks, tuned at the fundamental and the third harmonic components for the source voltage and four SOGI blocks, tuned at the fundamental, third, fifth and seventh harmonic components for the load current are used.

III. Current Controller Design

The filter voltage according to Fig. 1 is calculated as

$$v_{inv} = r_L i_F + L\frac{di_F}{dt} + v_S \quad (14)$$

By applying the Laplace transform to (14), the transfer function of the injected filter current, $I_F(s)$ from $V_{inv}(s)$ and $V_S(s)$ is obtained as

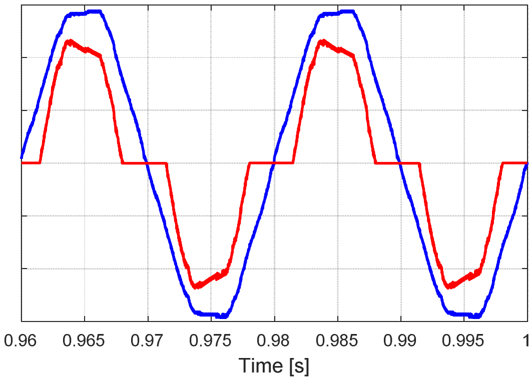

Fig. 6. Simulated source voltage (blue, 100V/div) and current (red, 10A/div) before compensation.

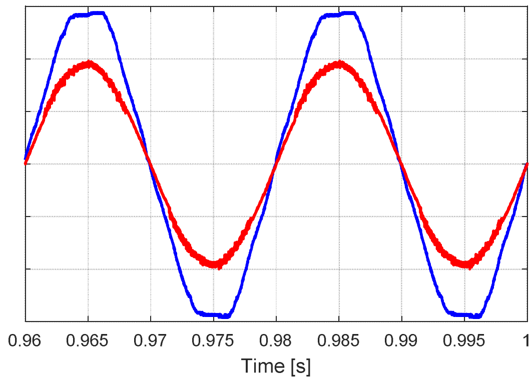

Fig. 8. Simulated source voltage (blue, 100V/div) and current (red, 10A/div) after compensation by the proposed method.

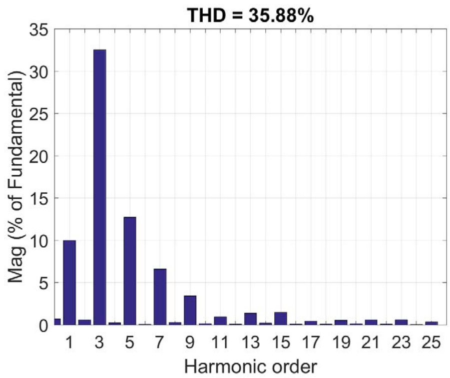

Fig. 7. Harmonic spectrum of the simulated source current of Fig. 6.

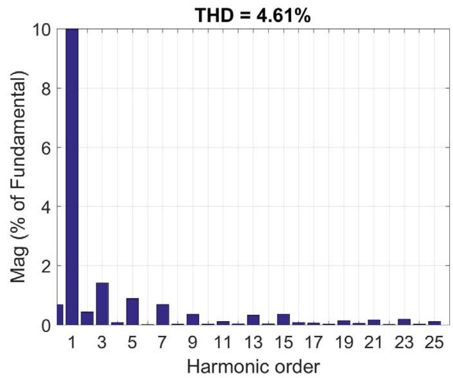

Fig. 9. Harmonic spectrum of the simulated source current of Fig. 8.

$$I_F(s) = \frac{1}{Ls + r_L}\left(V_{inv}(s) - V_S(s)\right) \tag{15}$$

Assuming that the inverter output voltage v_{inv} is generated from the difference of the filter current and its reference by using a proportional controller and the source voltage v_S is feedforwarded to the final control voltage v_{inv} (as shown in Fig. 2), then, the closed loop transfer function of the filter current control can be obtained as

$$G_{I_F}(s) = \frac{I_F(s)}{I_{F,ref}(s)} = \frac{K}{Ls + (r_L + K)} \tag{16}$$

where K is the proportional controller gain. By considering -3dB attenuation of (16) at the current control bandwidth frequency, ω_i, one can easily derive [1]

$$K = r_L + \sqrt{2r_L^2 + L^2\omega_i^2} \tag{17}$$

Because the inductor resistance r_L is very small, by ignoring this term, (17) is rewritten as

$$K = L\omega_i \tag{18}$$

It should be noted that the current control bandwidth can be selected in the range of ten times the grid frequency and one-tenth the switching frequency [3].

IV. Simulation and Experimental Results

In order to support the theoretical achievements, a single-phase shunt APF is constructed and connected to the electric distribution network at the point of common coupling (PCC). The parameters of the system are: L = 4mH, $C_1 = C_2$ = 4.4mF, v_S = 220V$_{rms}$, f = 50Hz and $f_{switching}$ = 10kHz. Figs. 6 and 7 show the simulated source voltage and current and harmonic spectrum of the source current, respectively. In this case, the load current is equal to the source current, because of disabling the APF. As can be seen, the load current harmonics are significant and its total harmonic distortion (THD) is about 35%. By enabling the APF, the source current THD decreases to 4.6% and its quality becomes much better. Figs. 8 and 9 shows the improvement. In order to compare the suggested reference current generation method with the conventional one, a simple all-pass filter, with the transfer function of (19), is used to generate the β-axis quantities from the original α-axis quantities. In (19), ω_f is the grid frequency. By substituting these variables into (10), the compensated source current and its harmonic spectrum are shown in Figs. 10 and 11. As can be seen, the source current distortion is very high and its THD is equal to 17.57%.

$$\frac{X_\beta(s)}{X_\alpha(s)} = \frac{\omega_f - s}{\omega_f + s} \tag{19}$$

The experimental results are given in Figs. 12 to 15. Fig. 12 shows the source voltage and current when the APF is disabled. The source voltage THD is equal to 4.6%. The load current harmonic spectrum is shown in Fig. 13 and its THD is about 35%. Figs. 14 and 15 show the source voltage and the compensated source current and its harmonic spectrum by the proposed method. As can be seen in these figures, the APF can improve the current THD and power quality, as already

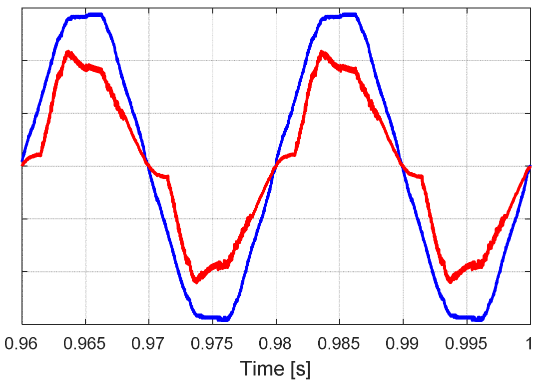

Fig. 10. Simulated source voltage (blue, 100V/div) and source current (red, 10A/div) after compensation by the conventional method.

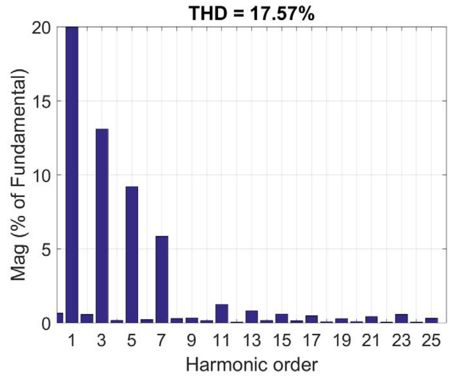

Fig. 11. Harmonic spectrum of the simulated source current of Fig. 10.

expected from the simulations. These results confirm appropriate performance of the proposed technique in a real electric distribution network.

V. Conclusion

This paper proposed design and implementation of a single-phase shunt APF based on the PQ theory for current harmonic compensation in electric distribution networks. The PQ theory is based on the SOGI structure, which is used to extract the filtered αβ components of the source voltage and load current. The design procedure of the reference extraction and the control algorithm is illustrated in details. The simulation and experimental results confirm excellent performance of the suggested method in a real distribution network.

References

[1] M.-S. Karbasforooshan, and M. Monfared, "An adaptive recursive discrete Fourier transform technique for the reference current generation of single-phase shunt active power filters," in *2016 7th Power Electron. Drive Syst. Technol. Conf. (PEDSTC)*, pp. 253-259, Feb. 2016.

[2] H. Akagi, Y. Kanazawa, and A. Nabae, "Instantaneous reactive power compensators comprising switching devices without energy storage components," *IEEE Trans. Ind. Appl.*, vol. IA-20, no. 3, pp. 625-630, May 1984.

[3] S. Golestan, M. Monfared, and J. M. Guerrero, "Second order generalized integrator based reference current generation method for single-phase shunt active power filters under adverse grid conditions," in *2013. 4th Power Electron. Drive Syst. Technol. Conf. (PEDSTC)*, pp. 510-517, Feb. 2013.

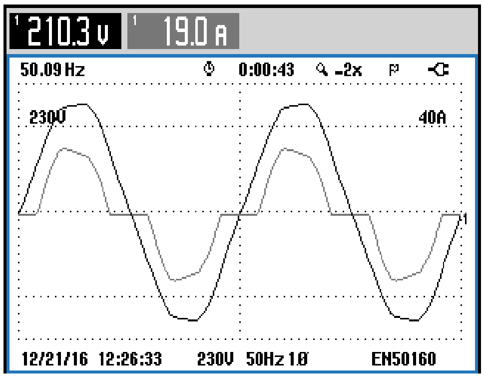

Fig. 12. Experimental source voltage and current before compensation.

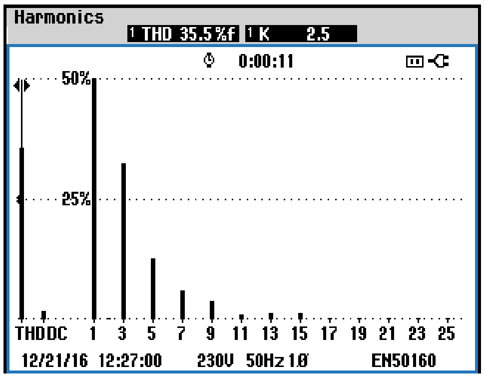

Fig. 13. Harmonic spectrum of the experimental source current of Fig. 12.

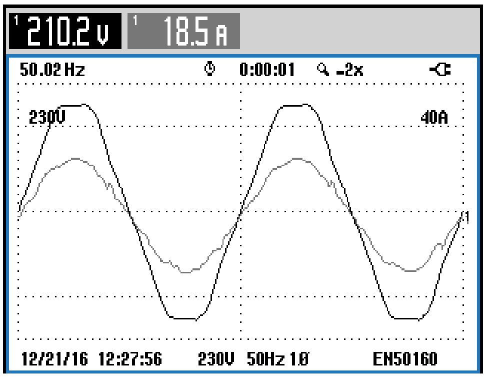

Fig. 14. Experimental source voltage and current after compensation.

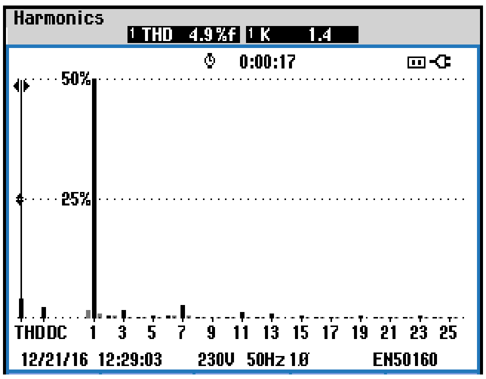

Fig. 15. Harmonic spectrum of the experimental source current of Fig. 14.

[4] V. Khadkikar, A. Chandra, and B. N. Singh, “Generalised single-phase p-q theory for active power filtering: simulation and DSP-based experimental investigation,” *IET Power Electron.*, vol. 2, no. 1, pp. 67-78, Jan. 2009.

[5] M. T. Haque, “Single-phase PQ theory for active filters” in *IEEE Reg. 10 Conf. Comput. Commun. Control Power Eng.*, no. 98, pp. 1941-1944, Oct. 2002.

[6] M. T. Haque, “Single-phase PQ theory,” in *2002 Annual IEEE 33rd Annual Power Electron. Special. Conf.*, no. 98. pp. 1815-1820, Jun. 2002.

[7] P. Rodriguez, A. Luna, I. Candela, R. Mujal, R. Teodorescu, and F. Blaabjerg, “Multiresonant frequency-locked loop for grid synchronization of power converters under distorted grid conditiond,” *IEEE Trans. Ind. Electron.*, vol. 58, no. 1, pp. 127-138, Jan. 2011.

[8] P. Rodríguez, A. Luna, R. S. Muñoz-Aguilar, I. Etxeberria-Otadui, R. Teodorescu, and F. Blaabjerg, “A stationary reference frame grid synchronization system for three-phase grid-connected power converters under adverse grid conditions,” *IEEE Trans. Power Electron.*, vol. 27, no. 1, pp. 99-112, Jan. 2012.