On the Use of the *p-q* Theory for Harmonic Currents Cancellation with Shunt Active Filter

Federico Martin SERRA[1], *Oscar Danilo MONTOYA*[2], *Cristian Hernan DE ANGELO*[3], *Daniel Gustavo FORCHETTI*[3]

[1]Laboratorio de Control Automatico, Facultad de Ingenieria y Ciencias Agropecuarias, Universidad Nacional de San Luis, Ruta 148 Ext. Norte, 5730 Villa Mercedes, San Luis, Argentina
[2]Ingenieria Electrica e Ingenieria Electronica, Facultad de Ingenieria, Universidad Tecnologica de Bolivar, Parque Industrial y Tecnologico Carlos Velez Pombo Km. 1 Via Turbaco, 131001 Cartagena, Colombia
[3]Grupo de Electronica Aplicada, Instituto de Investigaciones en Tecnologias Energeticas y Materiales, Facultad de Ingenieria, Universidad Nacional de Rio Cuarto, Ruta Nacional 36 Km. 601, X5804BYA Rio Cuarto, Argentina

fserra@ieee.org, o.d.montoyagiraldo@ieee.org, cdeangelo@ieee.org, dforchetti@ing.unrc.edu.ar

DOI: 10.15598/aeee.v17i3.3415

Abstract. *Discussion and mathematical proof on necessary and sufficient conditions for the application of the p-q theory for compensating the harmonic currents consumed by non-linear load using a shunt active filter are presented. These conditions over instantaneous active and reactive powers were not addressed before and must be considered on the design of new control strategies based on p-q theory. Theoretical demonstration is proposed and an application example with simulations results is used to validate the theoretical results.*

Keywords

Active filter control, harmonic compensation, p-q theory.

1. Introduction

Since late the 1960s, with the appearance of power electronic devices, the use of non-linear loads was increased significantly. In many cases, this kind of load represents a high percentage of the total load connected to the electric system [1], [2] and [3].

Non-linear loads consume high harmonic currents which must be supplied by the power source and transported by the transmission line increasing power losses due to parasitic resistance [4], [5] and [6]. Besides generating undesirable losses in the transmission line, the consumption of currents with high harmonics content is currently penalized by the power system operators [7] or affects the useful life of electrical machines [8]. For these reasons, eliminating harmonic components of the load current implies cost reduction in the system operation.

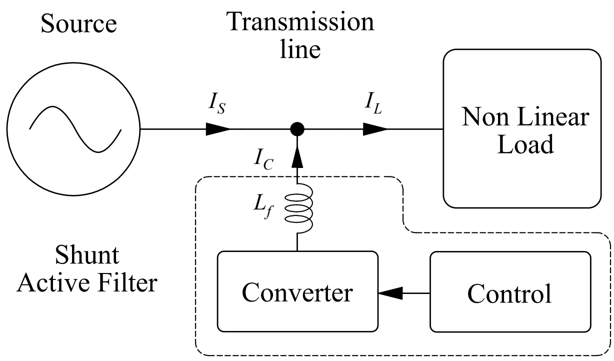

Fig. 1: Power System with shunt active filter.

One way of eliminating harmonic currents consumed from the power source by the load, even for unbalanced and/or distorted source voltages (V), is using a shunt active filter [9], [10], [11] and [12]. Shunt active filters are based on the injection of compensation currents (I_C) for canceling undesirable harmonics components of the current consumed from the source (I_S). Figure 1 shows a block diagram for the power system with a shunt active filter. Shunt active filters are composed by an electronic power converter, a passive filter (L_f) and a controller [4], [13] and [14]. Several control strategies have been proposed for shunt active filters based on the Instantaneous Active-Reactive Power theory [15], [16], [17] and [18], or simply the p-q

theory [19], [20]. Control based on this theory is intended to eliminate undesirable fundamental and harmonic current components from the source (harmonics elimination and reactive power compensation) while allowing the active and reactive power defined by control strategy to go through [21] and [22].

In the design of control strategies used to get sinusoidal currents from the source is assumed that the oscillating components of both real and imaginary powers, must be zero. In [4], several control strategies for Shunt Active Filters based in pq theory are proposed. In these strategies, the control objective is to cancel the oscillating components of the power; however, it is not mathematically proved that both power components, real and imaginary, must be null instead of only one of them to achieve sinusoidal current consumed from the power source.

This work proves mathematically that both oscillating power components must be zero in order for the control objective to be fulfilled. It also offers an example where only one of the power components is which shows clearly that this condition is not enough to fulfill the control objective.

The work is organized as follows: Sec. 2. describes the control of sinusoidal current using the *p*-*q* theory with a detail of the calculations for the compensation power. Section 3. contains an application example in which it can be clearly observed the necessity of annulling both power components in order to achieve the control objective. Finally, conclusions are given in Sec. 4. .

2. Control Strategy

The main goal of the control strategy is to compensate the load current (I_L) harmonic components so as to get a sinusoidal balanced current from power source (I_S) on a three wire unbalanced system where line voltages may have harmonic components.

This control objective can be described as:

$$\begin{gathered} I_S = I_S^{+1}, \\ (I_S^{-1} = I_S^{\pm n} = 0, \quad n = 2, 3, \ldots, \infty), \end{gathered} \tag{1}$$

where $I_S^{\pm n}$ is the positive $(+)$ or negative $(-)$ sequence component corresponding to the n^{th} harmonic component, whose frequency is n times the fundamental system frequency, ω [23].

2.1. Power Calculation

On balanced 3-wire systems with harmonic components, line voltages can be described on $\alpha\beta$ coordinates [24] as:

$$\begin{aligned} v_\alpha &= +\sqrt{3}\sum_{m=1}^{\infty} V^{+m}\sin(m\omega t + \phi^{+m}) + \ldots \\ &+\sqrt{3}\sum_{m=1}^{\infty} V^{-m}\sin(m\omega t + \phi^{-m}), \\ v_\beta &= -\sqrt{3}\sum_{m=1}^{\infty} V^{+m}\cos(m\omega t + \phi^{+m}) + \ldots \\ &+\sqrt{3}\sum_{m=1}^{\infty} V^{-m}\cos(m\omega t + \phi^{-m}), \end{aligned} \tag{2}$$

where m is m^{th} harmonic component of the line voltage and $\phi^{\pm m}$ is the phase angle of this component.

By considering the same degree of freedom as for the line voltages, line currents can be described as:

$$\begin{aligned} i_\alpha &= +\sqrt{3}\sum_{n=1}^{\infty} I^{+n}\sin(n\omega t + \delta^{+n}) + \ldots \\ &+\sqrt{3}\sum_{n=1}^{\infty} I^{-n}\sin(n\omega t + \delta^{-n}), \\ i_\beta &= -\sqrt{3}\sum_{n=1}^{\infty} I^{+n}\cos(n\omega t + \delta^{+n}) + \ldots \\ &+\sqrt{3}\sum_{n=1}^{\infty} I^{-n}\cos(n\omega t + \delta^{-n}), \end{aligned} \tag{3}$$

where n is used to name the n^{th} harmonic component of the current and $\delta^{\pm n}$ is thecorresponding phase angle.

Real and imaginary instantaneous powers (p and q) can be defined as [19]:

$$\begin{bmatrix} p \\ q \end{bmatrix} = \begin{bmatrix} v_\alpha & v_\beta \\ v_\beta & -v_\alpha \end{bmatrix} \cdot \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix}. \tag{4}$$

These real and imaginary instantaneous powers can be separated into two components:

$$\begin{aligned} p &= \bar{p} + \tilde{p}, \\ q &= \bar{q} + \tilde{q}, \end{aligned} \tag{5}$$

where $\bar{p}$ is defined as the constant real power, $\tilde{p}$ is defined as the oscillating real power, $\bar{q}$ is defined as the constant imaginary power, and $\tilde{q}$ is defined as the oscillating imaginary power. By replacing Eq. (2) and Eq. (3) in Eq. (4), $\bar{p}$, $\bar{q}$, $\tilde{p}$ and $\tilde{q}$ can be expressed as in Eq. (6), Eq. (7), Eq. (8) and Eq. (9), respectively (next page).

$$\bar{p} = 3\sum_{n=1}^{\infty} V^{+n} I^{+n} \cos(\phi^{+n} - \delta^{+n}) + 3\sum_{n=1}^{\infty} V^{-n} I^{-n} \cos(\phi^{-n} - \delta^{-n}), \tag{6}$$

$$\bar{q} = 3\sum_{n=1}^{\infty} V^{+n} I^{+n} \sin(\phi^{+n} - \delta^{+n}) - 3\sum_{n=1}^{\infty} V^{-n} I^{-n} \sin(\phi^{-n} - \delta^{-n}), \tag{7}$$

$$\begin{aligned} \tilde{p} = 3 &\sum_{m=1, m\neq n}^{\infty} \sum_{n=1}^{\infty} V^{+m} I^{+n} \cos((m-n)\omega t + \phi^{+m} - \delta^{+n}) + \ldots \\ +3 &\sum_{m=1, m\neq n}^{\infty} \sum_{n=1}^{\infty} V^{-m} I^{-n} \cos((m-n)\omega t + \phi^{-m} - \delta^{-n}) + \ldots \\ -3 &\sum_{m=1}^{\infty} \sum_{n=1}^{\infty} V^{+m} I^{-n} \cos((m+n)\omega t + \phi^{+m} + \delta^{-n}) + \ldots \\ -3 &\sum_{m=1}^{\infty} \sum_{n=1}^{\infty} V^{-m} I^{+n} \cos((m+n)\omega t + \phi^{-m} + \delta^{+n}), \end{aligned} \tag{8}$$

$$\begin{aligned} \tilde{q} = 3 &\sum_{m=1, m\neq n}^{\infty} \sum_{n=1}^{\infty} V^{+m} I^{+n} \sin((m-n)\omega t + \phi^{+m} - \delta^{+n}) + \ldots \\ -3 &\sum_{m=1, m\neq n}^{\infty} \sum_{n=1}^{\infty} V^{-m} I^{-n} \sin((m-n)\omega t + \phi^{-m} - \delta^{-n}) + \ldots \\ -3 &\sum_{m=1}^{\infty} \sum_{n=1}^{\infty} V^{+m} I^{-n} \sin((m+n)\omega t + \phi^{+m} + \delta^{-n}) + \ldots \\ +3 &\sum_{m=1}^{\infty} \sum_{n=1}^{\infty} V^{-m} I^{+n} \sin((m+n)\omega t + \phi^{-m} + \delta^{+n}). \end{aligned} \tag{9}$$

Considering only the positive sequence of the source voltage to fulfill the objective described in Eq. (1) the following powers are obtained:

$$\bar{p}^{+1} = 3V^{+1} I^{+1} \cos(\phi^{+1} - \delta^{+1}), \tag{10}$$

$$\bar{q}^{+1} = 3V^{+1} I^{+1} \sin(\phi^{+1} - \delta^{+1}), \tag{11}$$

$$\begin{aligned} \tilde{p}^{+1} = &+3V^{+1} \sum_{n=2}^{\infty} I^{+n} \cos((1-n)\omega t + \phi^{+1} - \delta^{+n}) + \\ &-3V^{+1} \sum_{n=1}^{\infty} I^{-n} \cos((1+n)\omega t + \phi^{+1} + \delta^{-n}), \end{aligned} \tag{12}$$

$$\begin{aligned} \tilde{q}^{+1} = &+3V^{+1} \sum_{n=2}^{\infty} I^{+n} \sin((1-n)\omega t + \phi^{+1} - \delta^{+n}) + \\ &-3V^{+1} \sum_{n=1}^{\infty} I^{-n} \sin((1+n)\omega t + \phi^{+1} + \delta^{-n}). \end{aligned} \tag{13}$$

where the superscript $+1$ is used to indicate that the power is calculated using the positive-sequence fundamental-frequency line voltage component V^{+1} and $\pm n$ is used to indicate that the power is calculated using V^{+1} with another, positive or negative-sequence, current component.

To obtain sinusoidal balanced source currents (I_S), Eq. (1) must be satisfied. From the point of view of real and imaginary powers, this control objective can be defined as:

$$I_S^{-1} = I_S^{\pm n} = 0 \quad \Rightarrow \quad \tilde{p}_S^{+1} = 0, \tag{14}$$

and also:

$$I_S^{-1} = I_S^{\pm n} = 0 \quad \Rightarrow \quad \tilde{q}_S^{+1} = 0, \tag{15}$$

where S subindex is used to indicate that the power is delivered by the power source.

Reciprocal of Eq. (14) or Eq. (15) are not necessarily true. However, if equations Eq. (14) and Eq. (15) are satisfied simultaneously, then sinusoidal balanced source currents can be guaranteed. This can be written as:

$$I_S^{-1} = I_S^{\pm n} = 0 \quad \Leftrightarrow \quad \tilde{p}_S^{+1} = \tilde{q}_S^{+1} = 0\,. \tag{16}$$

To demonstrate that both powers ($\tilde{p}_S^{+1}$ and $\tilde{q}_S^{+1}$) must be canceled to accomplish with Eq. (1), a detailed analysis of Eq. (12) and Eq. (13) must be performed.

Without loss of generality and to simplify the calculations, it is possible to assume that $\phi^{+1} = 0$. Then, by expanding Eq. (12) and Eq. (13) to $n = 7$ and regrouping terms of the same frequency, it is possible to write:

$$\begin{aligned}\tilde{p}^{+1} = [&+I^{+2}\cos(\omega t+\delta^{+2}) + I^{+3}\cos(2\omega t+\delta^{+3})+\\ &-I^{-1}\cos(2\omega t+\delta^{-1}) + I^{+4}\cos(3\omega t+\delta^{+4})+\\ &-I^{-2}\cos(3\omega t+\delta^{-2}) + I^{+5}\cos(4\omega t+\delta^{+5})+\\ &-I^{-3}\cos(4\omega t+\delta^{-3}) + I^{+6}\cos(5\omega t+\delta^{+6})+\\ &-I^{-4}\cos(5\omega t+\delta^{-4}) + I^{+7}\cos(6\omega t+\delta^{+7})+\\ &-I^{-5}\cos(6\omega t+\delta^{-5}) + \ldots]\,3\,V^{+1},\end{aligned} \tag{17}$$

$$\begin{aligned}\tilde{q}^{+1} = [&-I^{+2}\sin(\omega t+\delta^{+2}) - I^{+3}\sin(2\omega t+\delta^{+3})+\\ &-I^{-1}\sin(2\omega t+\delta^{-1}) - I^{+4}\sin(3\omega t+\delta^{+4})+\\ &-I^{-2}\sin(3\omega t+\delta^{-2}) - I^{+5}\sin(4\omega t+\delta^{+5})+\\ &-I^{-3}\sin(4\omega t+\delta^{-3}) - I^{+6}\sin(5\omega t+\delta^{+6})+\\ &-I^{-4}\sin(5\omega t+\delta^{-4}) - I^{+7}\sin(6\omega t+\delta^{+7})+\\ &-I^{-5}\sin(6\omega t+\delta^{-5}) - \ldots]\,3\,V^{+1}.\end{aligned} \tag{18}$$

On Eq. (17) and Eq. (18), it can be seen that the first term containing I^{+2} can be canceled by canceling either real or imaginary oscillating power ($\tilde{p}^{+1} = 0$ or $\tilde{q}^{+1} = 0$), since it is the only term with frequency ω. However, for the remaining terms of the series, this does not happens.

As an example, it can be seen on the last row of Eq. (17) that if $I^{+7} = I^{-5}$ and $\delta^{+7} = \delta^{-5}$ then:

$$+\,I^{+7}\cos(6\omega t+\delta^{+7}) - I^{-5}\cos(6\omega t+\delta^{-5}) = 0, \tag{19}$$

but from Eq. (18), it can be seen that:

$$-\,I^{+7}\sin(6\omega t+\delta^{+7}) - I^{-5}\sin(6\omega t+\delta^{-5}) \neq 0. \tag{20}$$

Then, if the line currents contain these harmonic components, the oscillating real power will be identically null ($\tilde{p}^{+1} = 0$) even when the line current is not sinusoidal ($I^{+7} = I^{-5} \neq 0$). However, in this case, the oscillating imaginary power will not be null ($\tilde{q}^{+1} \neq 0$).

To prove that there is not harmonic components combination that fulfills simultaneously that $\tilde{p}^{+1} = 0$ and $\tilde{q}^{+1} = 0$, a generic expression for each pair of terms of the same frequency of this powers can be written as:

$$\begin{aligned}&+I^{+(u+2)}\cos((u+1)\omega t+\delta^{+(u+2)}) + \ldots\\ &\quad -I^{-u}\cos((u+1)\omega t+\delta^{-u}) = 0,\end{aligned} \tag{21}$$

and

$$\begin{aligned}&-I^{+(u+2)}\sin((u+1)\omega t+\delta^{+(u+2)}) + \ldots\\ &\quad -I^{-u}\sin((u+1)\omega t+\delta^{-u}) = 0,\end{aligned} \tag{22}$$

where $u = 1, 2, \ldots, \infty$; (I^{+2} is not considered in these expressions).

The system formed by Eq. (21) and Eq. (22) can be written in matrix terms:

$$\mathbf{A}\mathbf{x} = \mathbf{0}, \tag{23}$$

with:

$$\mathbf{A} = \begin{bmatrix} \cos((u+1)\omega t+\delta^{+(u+2)}) & -\cos((u+1)\omega t+\delta^{-u}) \\ -\sin((u+1)\omega t+\delta^{+(u+2)}) & -\sin((u+1)\omega t+\delta^{-u}) \end{bmatrix}, \tag{24}$$

$$\mathbf{x} = \begin{bmatrix} I^{+(u+2)} \\ I^{-u} \end{bmatrix}, \quad \mathbf{0} = \begin{bmatrix} 0 \\ 0 \end{bmatrix}. \tag{25}$$

This algebraic system Eq. (23) has a unique solution ($\mathbf{x} = \mathbf{0}$) if matrix $\mathbf{A}$ is not singular ($\det(\mathbf{A}) \neq 0 \quad \forall t$), then:

$$\det(\mathbf{A}) = \sin(2(u+1)\omega t+\delta^{+(u+2)}+\delta^{-u}) \neq 0, \quad \forall t, \tag{26}$$

or:

$$2(u+1)\omega t+\delta^{+(u+2)}+\delta^{-u} = k\pi, \quad k = 1, 2, \ldots, \infty. \tag{27}$$

Since there is no combination of u, $\delta^{+(u+2)}$ and δ^{-u} which gives the trivial solution of Eq. (23), it is necessary that:

$$I^{+(u+2)} = I^{-u} = 0 \quad \Leftrightarrow \quad \tilde{p}_S^{+1} = \tilde{q}_S^{+1} = 0. \tag{28}$$

Then, the relationship stated in equation Eq. (16) is demonstrated.

2.2. Sinusoidal Current Control Strategy

The main goal of the proposed control strategy ($I_S = I_S^{+1}$) can be achieved using the control strategy proposed in [25], where sinusoidal and balanced source current is obtained if:

$$I_S^{-1} = I_S^{\pm n} = 0 \quad \Leftrightarrow \quad \tilde{p}_S^{+1} = \tilde{q}_S^{+1} = 0. \tag{29}$$

Besides, since no constant reactive power should be consumed from the source to minimize transmission line power losses, then:

$$\bar{q}_S^{+1} = 0. \tag{30}$$

With these restrictions, balanced and sinusoidal line current can be consumed from the source using an active shunt filter, where the power transferred by the filter (p_C^* y q_C^*) can be defined as:

$$\begin{aligned} p_C^* &= \tilde{p}_L^{+1},\\ q_C^* &= \bar{q}_L^{+1} + \tilde{q}_L^{+1} = q_L^{+1},\end{aligned} \tag{31}$$

where subindex L is used to indicate that powers are calculated using load line currents (I_L).

Compensating current references for the converter ($i^*_{C\alpha}$, $i^*_{C\beta}$) can be obtained (using p-q theory) as:

$$\begin{bmatrix} i^*_{C\alpha} \\ i^*_{C\beta} \end{bmatrix} = \frac{1}{(v_\alpha^{+1})^2 + (v_\beta^{+1})^2} \begin{bmatrix} v_\alpha^{+1} & v_\beta^{+1} \\ v_\beta^{+1} & -v_\alpha^{+1} \end{bmatrix} \begin{bmatrix} p^*_C \\ q^*_C \end{bmatrix}. \tag{32}$$

On Fig. 2, a block diagram of the proposed control strategy is shown. This control strategy uses a positive sequence detector (DSOGI-FLL) [26], [27], [28] and [29] to obtain the fundamental positive-sequence component of the line voltage (V^{+1}) which is used in real and imaginary power calculations (p_L^{+1} and q_L^{+1}). Figure 3 shows the block diagram of the DSOGI-FLL extracted from [28].

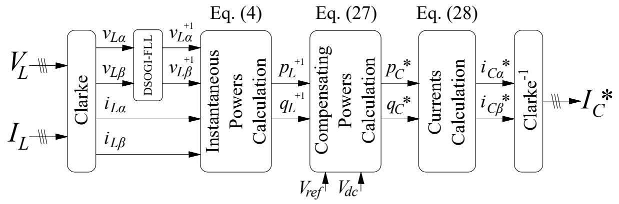

Fig. 2: Block diagram of the proposed strategy.

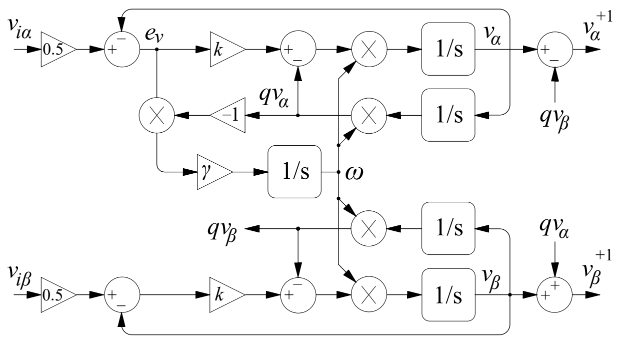

Fig. 3: Block diagram of the DSOGI-FLL extracted from [28].

3. Application Example

An application example is shown in this section where a particular case is analyzed. In this example, a sinusoidal balanced line voltage is considered ($V^{+1} = 1$ p.u.) but the line current is formed by a fundamental component in phase with the line voltage ($I_L^{+1} = 1$ p.u., and $\delta^{+1} = 0$), a 5^{th} negative-sequence harmonic component and a 7^{th} positive-sequence harmonic component with the same amplitude (0.1 p.u.) and phases $\delta^{-5} = \delta^{+7} = 0$:

$$\begin{aligned} I_L^{+1} = 1, \quad I_L^{-5} = I_L^{+7} = 0.1, \\ \delta^{+1} = \delta^{-5} = \delta^{+7} = 0. \end{aligned} \tag{33}$$

Then, the line voltages can be defined as in Eq. (2):

$$\begin{aligned} v_\alpha &= +\sqrt{3}\sin(\omega t), \\ v_\beta &= -\sqrt{3}\cos(\omega t), \end{aligned} \tag{34}$$

and the load line current will be:

$$\begin{aligned} i_{L\alpha} &= +\sqrt{3}\left[\sin(\omega t) + 0.1\sin(5\omega t) + 0.1\sin(7\omega t)\right], \\ i_{L\beta} &= -\sqrt{3}\left[\cos(\omega t) - 0.1\cos(5\omega t) + 0.1\cos(7\omega t)\right]. \end{aligned} \tag{35}$$

Then, the oscillating real power can be calculated using Eq. (12) as:

$$\tilde{p}^{+1} = -0.3\cos(6\omega t) + 0.3\cos(6\omega t) \equiv 0, \tag{36}$$

while the oscillating imaginary power is obtained from Eq. (13) as:

$$\tilde{q}^{+1} = -0.3\sin(6\omega t) - 0.3\sin(6\omega t), \tag{37}$$

then:

$$\tilde{q}^{+1} = 0.6\sin(6\omega t). \tag{38}$$

The line currents (I_{Sabc}) and the imaginary and real power provided by the power source (p^{+1} and q^{+1}) for the system without compensation are shown in Fig. 4(a) and Fig. 4(b). In Fig. 4(b) it can be seen that the oscillating real power is null since only constant real power is provided by the source ($\bar{p}^{+1} = 1$ p.u. and $\tilde{p}^{+1} = 0$). However, the imaginary oscillating power is not null ($\tilde{q}^{+1} \neq 0$), as was determined by Eq. (38).

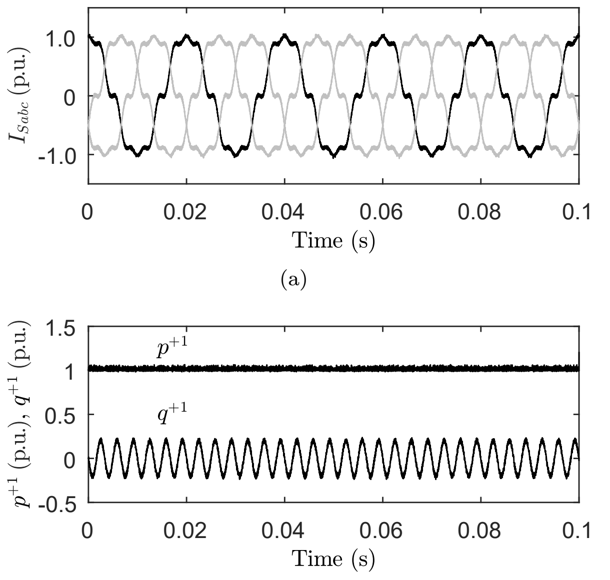

Fig. 4: System with no compensation.

If, for this example, only the oscillating real power $\tilde{p}^{+1}$ is compensated, the source currents (I_{Sabc}) will still be nonsinusoidal, as shown in Fig. 5(a). Figure 5(b) shows the imaginary and real power provided by the power source (p^{+1} and q^{+1}) for this case. From these results, it is possible to see that compensating only the oscillating part of the real or imaginary power does not guarantee that the line current satisfies Eq. (1).

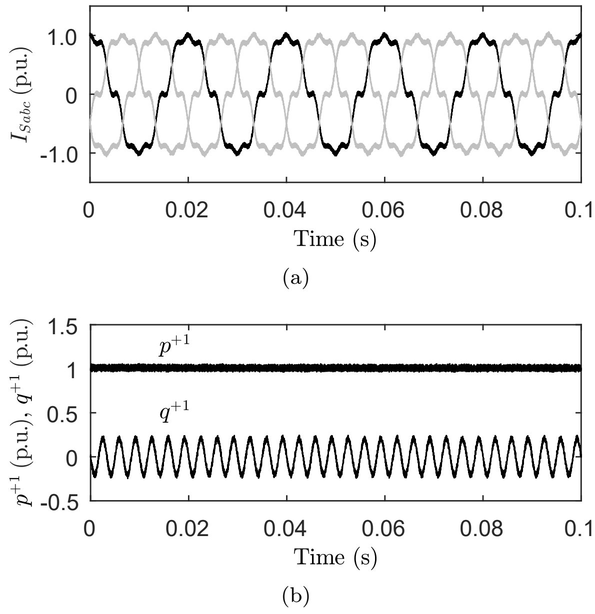

Fig. 5: System with compensation $\tilde{p}^{+1} = 0$.

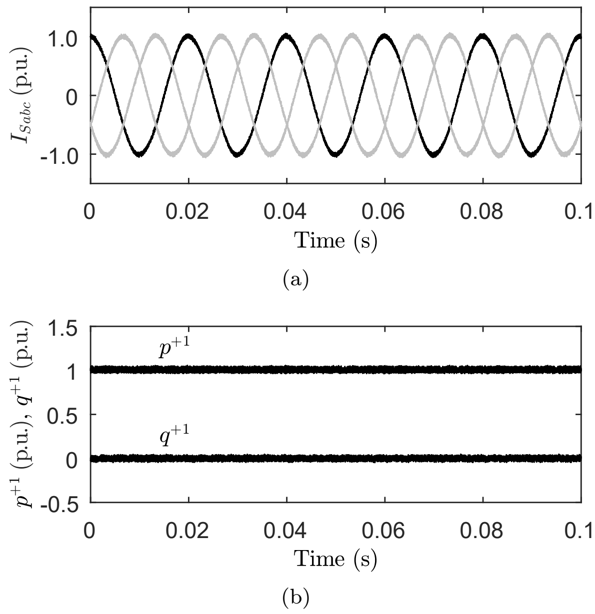

Fig. 6: System with compensation $\tilde{p}^{+1} = 0$ and $\tilde{q}^{+1} = 0$.

Finally, Fig. 6(a) and Fig. 6(b) show the line currents (I_{Sabc}) and the imaginary and real power supplied by the power source (p^{+1} and q^{+1}) with the control strategy compensating $\tilde{p}^{+1} = 0$ and $\tilde{q}^{+1} = 0$. As it can be appreciated, only when both oscillating powers are compensated, the control objective is achieved, obtaining sinusoidal balanced source current. In Fig. 6(b) can be seen that the oscillating real and imaginary powers are null, while only constant real power is supplied ($\bar{p}^{+1} = 1\,p.u.$ and $\tilde{p}^{+1} = \tilde{q}^{+1} = 0$).

From all these results, it can be seen that the oscillating power $\tilde{p}^{+1}$ is null in all cases, even when the source current is nonsinusoidal. However, the oscillating imaginary power is zero only when both oscillating powers are compensated, which gives sinusoidal balanced source currents.

Similar simulation can be performed using an appropriate selection of amplitudes an phases to show that compensating only $\tilde{q}^{+1}$ a sinusoidal balanced source current cannot be guaranteed.

4. Conclusions

A detailed discussion and mathematical proof on specific topics of p-q theory were performed in this work. From the power definitions and a generalized analysis, necessary conditions for current compensation using a shunt active filter were stated. Such conditions were not addressed in previous works, but they must be considered in the design stage of this kind of control strategies. Simulation results that validate the theoretical analysis are included.

References

[1] AKAGI, H. Control strategy and site selection of a shunt active filter for damping of harmonic propagation in power distribution systems. *IEEE Transactions Power Delivery*. 1997, vol. 12, iss. 1, pp. 354–363, ISSN 1937-4208. DOI: 10.1109/61.568259.

[2] MOHAN, N., T. M. UNDELAND and W. P. ROBBINS. *Power Electronics: Converters, Applications, and Design*. 3rd ed. New York: Wiley, 2003. ISBN 978-04-712-2693-2.

[3] KARIMAPOUR, D. and F. R. SALMASI. Stability Analysis of AC Microgrids With Constant Power Loads Based on Popov's Absolute Stability Criterion. *IEEE Transactions on Circuits and Systems II: Express Briefs*. 2015, vol. 62, iss. 7, pp. 696–700, ISSN 1558-3791. DOI: 10.1109/TCSII.2015.2406353.

[4] AKAGI, H., E. H. WATANABE and M. AREDES. *Instantaneous Power Theory and Applications to Power Conditioning*. 2nd ed. New York: Wiley, 2017. ISBN 978-11-193-0718-1. DOI: 10.1002/9781119307181.

[5] HUANG, C.-H. and C.-H. LIN. Multiple harmonic-source classification using a Self-Organization Feature Map network with voltage-current wavelet transformation patterns. *Applied Mathematical Modelling*. 2015, vol. 39, iss. 19, pp. 5849–5861, ISSN 0307-904X. DOI: 10.1016/j.apm.2015.03.045.

[6] TIEN, D. V., R. GONO, Z. LEONOWICZ and P. KREJCI. Load Flow Analysis in Power System Network Incorporating STATCOM: A Comparison of the Direct and Indirect Algorithm of the Newton-Raphson Method. *Advances in Electrical and Electronic Engineering*. 2019, vol. 17, iss. 1, pp. 13–23. ISSN 1804-3119. DOI: 10.15598/aeee.v17i1.3054.

[7] BOSCH, S., J. STAIGER and H. STEINHART. Predictive Current Control for an Active Power Filter With LCL-Filter. *IEEE Transactions on Industrial Electronics*. 2017, vol. 65, iss. 6, pp. 4943–4952, ISSN 1557-9948. DOI: 10.1109/TIE.2017.2772176.

[8] KINDL, V. and M. HAJZMAN. Identification of harmful time harmonic interactions in a high power squirrel-cage traction machine. *Applied Mathematical Modelling*. 2014, vol. 38, iss. 24, pp. 6153–6169, 2014, ISSN 0307-904X. DOI: 10.1016/j.apm.2014.05.013.

[9] HAMOUDI, F. and H. AMIMEU. Analysis and Sliding Mode Control of Four-Wire Three-Leg Shunt Active Power Filter. *Advances in Electrical and Electronic Engineering*. 2015, vol. 13, iss. 5, pp. 430–441. ISSN 1804-3119. DOI: DOI: 10.15598/aeee.v13i5.1344.

[10] WATANABE, E. H., H. AKAGI and M. AREDES. Instantaneous p-q power Theory for compensating nonsinusoidal systems. In: *2008 International School on Nonsinusoidal Currents and Compensation*. Lagow: IEEE, 2008, pp. 1–10. ISBN 978-1-4244-2130-5. DOI: 10.1109/ISNCC.2008.4627480.

[11] AKAGI, H. New trends in active filters for power conditioning. *IEEE Transaction on Industrial Applications*. 1996, vol. 32, iss. 6, pp. 1312–1322, ISSN 1939-9367. DOI: 10.1109/28.556633.

[12] FERREIRA, F., L. MONTEIRO, J. L. AFONSO and C. COUTO. A control strategy for a three-phase four-wire shunt active filter. In: *2008 34th Annual Conference of IEEE Industrial Electronics*. Orlando: IEEE, 2008, pp. 411–416. ISBN 978-1-4244-1766-7. DOI: 10.1109/IECON.2008.4757989.

[13] SERRA, F. M., C. H. DE-ANGELO and D. G. FORCHETTI. Application of the modified IDA-PBC for shunt active power filters control. *International Journal of Circuit Theory and Applications*. 2016, vol. 44, iss. 9, pp. 1717–1729, ISSN 1097-007X. DOI: 10.1002/cta.2189.

[14] WU, T.-F., H.-C. HSIEH, C.-W. HSU and Y.-R. CHANG. Three-Phase Three-Wire Active Power Filter With D-Σ Digital Control to Accommodate Filter-Inductance Variation. *IEEE Journal of Emerging and Selected Topics in Power Electronics*. 2015, vol. 4, iss. 1, pp. 44–53, ISSN 2168-6785. DOI: 10.1109/JESTPE.2015.2498189.

[15] BHATTACHARYA, A., C. CHAKRABORTY and S. BHATTACHARYA. Shunt Compensation. *IEEE Industrial Electronics Magazine*. 2009, vol. 3, iss. 3, pp. 38–49, ISSN 1941-0115. DOI: 10.1109/MIE.2009.933881.

[16] VALOUCH. V. Active filter control methods based on different power theories. In: *ISIE'99. Proceedings of the IEEE International Symposium on Industrial Electronics (Cat. No. 99TH8465)*. Bled: IEEE, pp. 521–526. ISBN 0-7803-5662-4. DOI: 10.1109/ISIE.1999.798666.

[17] BUSO, S., L. MALESANI and P. MATTAVELLI. Comparison of current control techniques for active filter applications. *IEEE Transactions on Industrial Electronics*. 1998, vol. 45, iss. 5, pp. 722–729, ISSN 1557-9948. DOI: 10.1109/41.720328.

[18] AREDES, M., J. HAFNER and K. HEUMANN. Three-phase four-wire shunt active filter control strategies. *IEEE Transactions on Industrial Electronics*. 1997, vol. 12, iss. 2, pp. 311–318, ISSN 1941-0107. DOI: 10.1109/63.558748.

[19] PENG, F. Z. and J.-S. LAI. Generalized instantaneous reactive power theory for three-phase power systems. *IEEE Transactions on Instrumentation and Measurement*. 1996, vol. 45, iss. 1, pp. 293–297, ISSN 1557-9662. DOI: 10.1109/19.481350.

[20] BOUSSAID, A., A. L. NEMMOUR, L. LOUZE and A. KHEZZAR. A novel strategy for shunt active filter control. *Electric Power Systems Research*. 2015, vol. 123, iss. 1, pp. 154–163, ISSN 0378-7796. DOI: 10.1016/j.epsr.2015.02.008.

[21] DEVASSY, S. and B. SINGH. Control of a Solar Photovoltaic Integrated Universal Active Power Filter Based on a Discrete Adaptive Filter. *IEEE Transactions on Industrial Informatics*. 2018, vol. 14, iss. 7, pp. 3003–3012, ISSN 1941-0050. DOI: 10.1109/TII.2017.2778346.

[22] FERREIRA, S. C., R. B. GONZATTI, R. R. PEREIRA, C. H. DA SILVA, L. E. B. DA SILVA and G. LAMBERT-TORRES. Finite Control Set Model Predictive Control for Dynamic Reactive Power Compensation With Hybrid Active Power Filters. *IEEE Transactions on Industrial Electronics*. 2018, vol. 65, iss. 3, pp. 2608–2617, ISSN 1557-9948. DOI: 10.1109/TIE.2017.2740819.

[23] BAYLISS, C. R. and B. J. HARDY. *Transmission and Distribution Electrical Engineering*. 3rd ed. Oxford: Elsevier, 2006. ISBN 978-0-7506-6673-2.

[24] KRAUSE, P., O. WASYNCZUK, T. O'CONNELL and M. HASAN. *Introduction to Electric Power and Drive Systems*. 1st ed. New York: Wiley, 2017. ISBN 978-1-119-21425-0.

[25] MOUSSA, H., J.-P. MARTIN, S. PIERFEDERICI, F. MEIBODY-TABAR and N. MOUBAYED. Voltage harmonic distortion compensation with non-linear load power sharing in low-voltage islanded microgrid. *Mathematics and Computers in Simulation*. 2018, vol. 158, iss. 1, pp. 32–48, ISSN 0378-4754. DOI: 10.1016/j.matcom.2018.05.007.

[26] RODRIGUEZ, P., A. LUNA, M. CIOBOTARU, R. TEODURESCU and F. BLAABJERG. Advanced Grid Synchronization System for Power Converters under Unbalanced and Distorted Operating Conditions. In: *32nd Annual Conference on IEEE Industrial Electronics (IECON 2006)*. Paris: IEEE, 2006, pp. 5173–5178. ISBN 978-1-5090-9155-3. DOI: 10.1109/IECON.2006.347807.

[27] AREDES, M., H. AKAGI, E. H. WATANABE, E. V. SALGADO and L. F. EENCARNACAO. Comparisons Between the p-q and p-q-r Theories in Three-Phase Four-Wire Systems. *IEEE Transactions on Power Electronics*. 2009, vol. 24, iss. 4, pp. 924–933. ISSN 1941-0107. DOI: 10.1109/TPEL.2008.2008187.

[28] SERRA, F. M., D. G. FORCHETTI and C. H. DE ANGELO. Comparison of positive sequence detectors for shunt active filter control. In: *2010 9th IEEE/IAS International Conference on Industry Applications (INDUSCON 2010)*. Sao Paulo: IEEE, pp. 1–6. ISBN 978-1-4244-8009-8. DOI: 10.1109/INDUSCON.2010.5739965.

[29] CURTI, M. R., F. M. SERRA, D. G. FORCHETTI and C. H. DE ANGELO. Experimental Implementation of PSDs. In: *2012 10th IEEE/IAS International Conference on Industry Applications (INDUSCON 2012)*. Fortaleza: IEEE, pp. 1–6. ISBN 978-1-4673-2411-3. DOI: 10.1109/INDUSCON.2012.6451650.

About Authors

Federico Martin SERRA was born in Villa Mercedes, Argentina, in 1981. He received the Electrical and Electronic Engineer degree from the Universidad Nacional de San Luis, Argentina, in 2007, and the Doctor of Engineering degree from the Universidad Nacional de Rio Cuarto, Argentina, in 2013. Since 2012 he is Director of the Laboratory of Automatic Control (LCA) in the Universidad Nacional de San Luis. He is currently a Professor at the Universidad Nacional de San Luis and Assistant Researcher at Consejo Nacional de Investigaciones Cientificas y Tecnicas (CONICET), Argentina. His research interests include modeling and advanced control of power converters in applications of microgrids, electric vehicles and renewable energy conversion systems.

Oscar Danilo MONTOYA was born in Obando, Valle, Colombia. He received his B.Sc., M.Sc. and Ph.D degrees in Electrical Engineering from Universidad Tecnologica de Pereira, Colombia, in 2012, 2014 and 2019, respectively. He is currently working as an assistant professor at the Electrical Engineering Program at Universidad Tecnolgica de Bolivar. His research interests include mathematical optimization, planning and control of power systems, renewable energy, energy storage, protective devices, passivity-based control, and dynamical analysis.

Cristian Hernan de ANGELO received the Electrical Engineer degree from the Universidad Nacional de Rio Cuarto, Argentina, in 1999, and the Dr. of Engineering degree from the Universidad Nacional de La Plata, Argentina, in 2004. In 1994, he joined the Grupo de Electronica Aplicada, Universidad Nacional de Rio Cuarto. He is currently Associate Professor at Universidad Nacional de Rio Cuarto and Principal Researcher at Consejo Nacional de Investigaciones Cientificas y Tecnicas, Argentina. His research interests include electric and hybrid vehicles, fault diagnosis on electric machines, electric motors control, and renewable-energy generation.

Daniel Gustavo FORCHETTI was born in Rosario, Argentina, in 1975. He received the Electrical Engineer degree from the Universidad Nacional de Rio Cuarto, Rio Cuarto, Argentina, in 1999, and the Doctor of Engineering degree from the Universidad Nacional de La Plata, La Plata, Argentina, in 2010. Since 1996, he has been with the Grupo de Electronica Aplicada, Universidad Nacional de Rio Cuarto. He is also with the Consejo Nacional de Investigaciones Cientificas y Tecnicas, Buenos Aires, Argentina. His research interests include electric generator control, sensorless induction machine control, and renewable energy generation.