Active Power Filters: A Comparative Analysis of Current Control Techniques for Four-Leg Full-Bridge Voltage Source Inverters

Juan Rueda, Ernesto Pieruccini, María Mantilla, *Member, IEEE* and Johann Petit, *Member, IEEE*

Abstract— This paper presents a comparative analysis between three current control techniques used to obtain the firing pulses of Four-Leg Full-Bridge Voltage Source Inverters (FLFB-VSI), for shunt active power filters applications. The discussed techniques correspond to the Delta Modulation, the Proportional Integral (PI) regulator and the Deadbeat controller. The main purpose is to analyze the performance of each technique in the tracking of unbalanced and distorted current references including homopolar sequence components. The algorithms performance is evaluated through some simulations in ATP and the comparative analysis is based on some criteria such as the maximum steady state error and the effective error of the current generated by the inverter. It can be concluded that the Deadbeat controller presents the lowest tracking error of the three techniques for the FLFB-VSI topology.

***Index Terms*—Active power filters, current control techniques, Four-Leg Full-Bridge Voltage Source Inverters (FLFB-VSI), power quality.**

I. Introduction

In recent years, the increase of nonlinear power electronic devices and the massive use of industrial machines and automation devices, have led to a significant increase of disturbances in distribution systems like current and voltage distortion, current unbalance, excessive neutral return currents, poor power factor and others [1]. One of the solutions for this problem is the use of active compensation devices, better known as Active Power Filters (APF) [2].

An APF is a device based on power electronics used to improve power quality in distribution systems. This paper is focused specifically on active power filters of shunt connection, which are usually used for harmonics mitigation, power factor correction and load balancing [2], [3]. A general scheme of a shunt active power filter is shown in Fig. 1. Its main components are a power inverter, a connection filter and a control system [4]. The point when the APF is connected to the distribution network is called the Point of Common Coupling (PCC).

Regarding the inverter topology, it can be classified according to the converter type and the number of the phases and wires of the system. One of these topologies corresponds to the Four-Leg Full-Bridge Voltage Source Inverter (FLFB-VSI), which is the topology that is considered in this paper. This topology can be used in four-wire systems, allowing the compensation of zero sequence currents [5].

On the other hand, the APF control system consists of three loops: the current reference generator, the DC voltage regulator and the current controller. Justly, this paper is focus in the last control loop used to calculate the power inverter firing pulses such that the injected current follows the current reference [6].

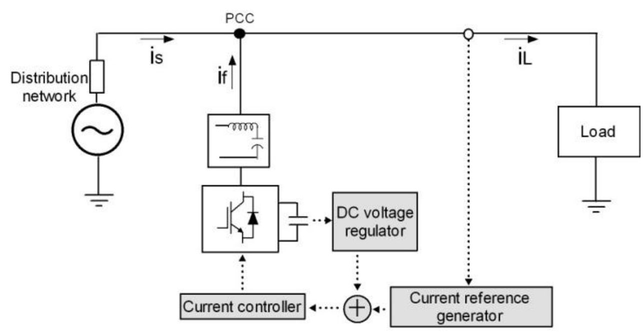

Fig 1. General scheme of a shunt active power filter.

In this way, the reference signals tracking by using three different current control techniques (Delta Modulation, the Proportional Integral (PI) regulator and the Deadbeat controller) is evaluated by ATP simulations for the FLFB-VSI topology. The algorithms performance is shown when they are used to follow two different kinds of current references. The first reference corresponds to distorted and unbalanced currents and the second one considers unbalanced currents with homopolar sequence components.

Furthermore, a comparative analysis between the three current control techniques is presented based on some criteria such as the maximum steady state error and the effective error of the current generated by the inverter.

The organization of the paper is as follows. Section II presents a brief description of the FLFB-VSI topology.

Section III presents the current control algorithms. The reference currents for the two cases are shown in section IV. Section V shows the simulation results and the comparative analysis. Finally, the main conclusions of the work are presented.

II. Power Inverter Topology

In three-phase four-wire systems when it is required the injection of high homopolar sequence currents, the Four-Leg Full-Bridge Voltage Source Inverter (FLFB-VSI) topology can be used. Fig. 2 shows the FLFB-VSI topology considering the semiconductor devices as ideal switches. The topology is connected to the equivalent of the distribution network at the PCC via an inductive filter.

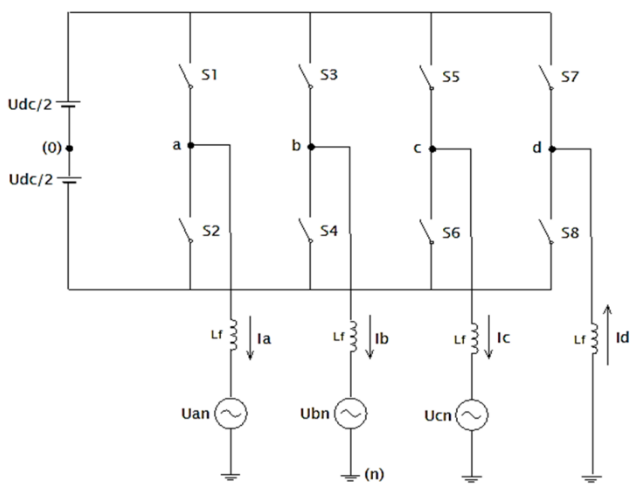

Fig. 2. Four-Leg Full-Bridge Voltage Source Inverter.

The FLFB-VSI topology contains an additional leg compared with the traditional Three-Phase Full-Bridge Inverter. This additional leg can be connected to the neutral of the load which allows a path for homopolar sequence currents. Also, this topology can take full advantage of the total DC bus voltage [5].

III. Current Control Techniques

The current control techniques are used to calculate the power inverter firing pulses such that the injected current follows the current reference. Some techniques used to this purpose are the Delta Modulation, the PI regulator and the Deadbeat controller [6]. These techniques can be classified as linear or nonlinear controllers. The PI regulator and the Deadbeat controller correspond to the linear group, and the Delta Modulation corresponds to the nonlinear group [6], [7].

In the linear controllers, the inverter output voltage is calculated based on the tracking error. Then, this voltage is synthesized through an open-loop technique in order to determine the inverter firing pulses. In this paper Pulse Width Modulation (PWM) is used as the open loop control technique [8]. On the other hand, the nonlinear controllers obtain directly the switching signals from the error signal [6].

A. Delta Modulation

This technique is a particular case of the hysteresis controller considering a null tolerance band and a fixed switching frequency [4]. In this way, this controller compares the current reference with the current generated by the inverter, in each sampling instant. Thus, if the mismatch between the actual generated current is greater than the current reference, the inverter voltage output must be positive and if the mismatch is negative, the inverter voltage output must be negative [6], [9].

Equation (1) presents an approach for the current injected by the *k*-leg of the inverter ($i_k(t)$ for $k = a, b, c$) with the Delta Modulation controller, considering that the voltage in PCC remains constant during a sampling period [1], [7]. Also, equation (2) presents an expression for the current injected by the *d*-leg of the inverter.

$$i_k(t) = \frac{u_{kinv}(t) - u_{kn}(t) - u_{no}(t)}{L_f} t + i_k(t_o) \qquad (1)$$

$$i_d(t) = \frac{u_{no}(t) - u_{dinv}(t)}{L_f} t + i_d(t_o) \qquad (2)$$

Where $\mathrm{u_{no}}(\mathrm{t})$ is the floating voltage between the neutral of the network and the midpoint of the dc side, L_f is the inductance of the connection filter, $\mathrm{u_{kn}}(\mathrm{t})$ is the voltage at the PCC for the *k*-leg ($k = a, b, c$), $i_k(t_o)$ is the current at the initial of the sampling period and $\mathrm{u_{kinv}}(\mathrm{t})$ is the inverter output voltage with respect to the midpoint of the dc side for the k-leg ($k = a, b, c, d$). Equation (1) represents a straight line with slope *m*, as follows:

$$m = \frac{u_{kinv}(t) - u_{kn}(t) - u_{no}(t)}{L_f} \qquad (3)$$

Accordingly, the current slope depends on the difference between $\mathrm{u_{kinv}}(\mathrm{t})$ and $\mathrm{u_{kn}}(\mathrm{t})$, and the value of $\mathrm{u_{no}}(\mathrm{t})$.

B. Proportional Integral (PI) Regulator

The discrete model of the PI regulator for the *k*-leg ($k = a, b, c$) of the power inverter is presented in equation (4), where $e_k(n)$ is the error between the current reference and the generated current, $u_{kinv}(n)$ is the inverter output voltage, T_{sw} is the sampling period, k_p is the proportional gain and T_i is the integral time representing the number of times that the proportional action is repeated. This equation defines the inverter output voltage based on the tracking error [9].

$$u_{kinv}(n) = k_p[e_k(n) - e_k(n-1)] + \frac{k_p}{T_i} e_k(n) T_{sw} + u_{kinv}(n-1) \quad \therefore \quad k = a, b, c, d \qquad (4)$$

C. Deadbeat controller

This technique calculates the inverter output voltage necessary to reach the current reference by the end of the next modulation period. The algorithm is based on the discrete model of the system, the system parameters and the tracking error [7].

The inverter output voltage is determined using the discrete model of the grid-tied FLFB-VSI topology presented in Fig. 2. The discrete model is calculated by using the bilinear transformation. The resulting algorithm is presented in equations (5) and (6), for legs *a*,*b*,*c* and leg *d*, respectively.

$$u_{kinv}(n) = \frac{L_f}{T_{sw}} e_k(n) + \frac{L_f}{T_{sw}} e_d(n) + u_{kn}(n) \quad \therefore \quad k = \{a, b, c\} \qquad (5)$$

$$u_{dinv}(n) = -\frac{L_f}{T_{sw}} e_d(n) - \frac{1}{2}[u_{on}(n) + u_{on}(n+1)] \qquad (6)$$

D. Pulse Width Modulation (PWM)

The inverter output voltage obtained by using the Deadbeat controller or the PI regulator is synthesized through the Pulse Width Modulation (PWM) technique. This technique determines the width of the firing pulses in a way that the mean value of the generated voltage equals the mean value of the reference voltage during each sampling period [8].

In this paper is used the regular sampled PWM, so the switching is made at the intersection between the regularly sampled reference inverter voltage and a high-frequency triangular carrier (see Fig. 3).

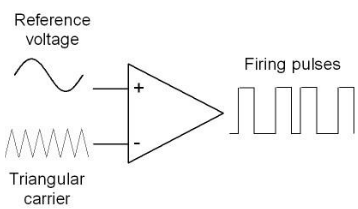

Fig. 3. Pulse Width Modulation (PWM).

IV. Reference Currents

The algorithms performance was evaluated for two reference currents. The first reference corresponds to distorted and unbalanced currents and the second one considers unbalanced currents with homopolar sequence components.

A. Case I: Unbalanced and distorted currents

In this case is considered a three-phase reference current containing three components as shown in equations (7)-(9). The first one corresponds to a fundamental sinusoidal component (60Hz) with amplitude of 2,4 [A] and a phase angle of 90 degrees with respect to the network phase angle. The second is a negative sequence component at 60 Hz with amplitude of 1,8 [A]. Finally, the third component corresponds to a fifth harmonic with amplitude of 0,8 [A] generated by a nonlinear load. In addition, the reference for the current by the *d*-leg is shown in equation (10).

$$i_{refa}(t) = 2{,}4\sin\left(120\pi t + \frac{\pi}{2}\right) + 1{,}8\sin\left(120\pi t + \frac{5\pi}{18}\right) - 0{,}8\sin\left(600\pi t + \frac{\pi}{6}\right)[A] \qquad (7)$$

$$i_{refb}(t) = 2{,}4\sin\left(120\pi t - \frac{\pi}{6}\right) + 1{,}8\sin\left(120\pi t + \frac{17\pi}{18}\right) - 0{,}8\sin\left(600\pi t + \frac{5\pi}{6}\right)[A] \qquad (8)$$

$$i_{refc}(t) = 2{,}4\sin\left(120\pi t + \frac{7\pi}{6}\right) + 1{,}8\sin\left(120\pi t - \frac{7\pi}{18}\right) - 0{,}8\sin\left(600\pi t - \frac{\pi}{2}\right)[A] \qquad (9)$$

$$i_{refd}(t) = i_{refa}(t) + i_{refb}(t) + i_{refc} = 0 \qquad (10)$$

B. Case II: Unbalanced currents with homopolar sequence components

In order to test the FLFB-VSI topology and the controllers in the injection of unbalanced currents with homopolar sequence components, it is arbitrarily taken the reference signals presented in equations (11)-(14). These references have three components. The first component corresponds to a positive sequence current at the fundamental frequency (60Hz) with amplitude of 2,25 [A] and a phase angle of 90 degrees with respect to the network phase angle. The second one is a negative sequence component at 60 Hz. The third component is a homopolar sequence current at the fundamental frequency with amplitude of 0,5 [A].

$$i_{refa}(t) = 2{,}25\sin\left(120\pi t + \frac{\pi}{2}\right) - \sin\left(120\pi t + \frac{\pi}{4}\right) + 0{,}5\sin(120\pi t)\,[A] \qquad (11)$$

$$i_{refb}(t) = 2{,}25\sin\left(120\pi t - \frac{\pi}{6}\right) - \sin\left(120\pi t + \frac{11\pi}{12}\right) + 0{,}5\sin(120\pi t)\,[A] \qquad (12)$$

$$i_{refc}(t) = 2{,}25\sin\left(120\pi t + \frac{7\pi}{6}\right) - \sin\left(120\pi t - \frac{5\pi}{12}\right) + 0{,}5\sin(120\pi t)\,[A] \qquad (13)$$

$$i_{refd}(t) = i_{refa}(t) + i_{refb}(t) + i_{refc}(t) = 1{,}5\sin(120\pi t)\,[A] \qquad (14)$$

V. Simulation Results

The algorithms performance was analyzed through some simulations in ATP. The simulation parameters, comparison criteria and results are presented below.

A. *Simulation parameters*

- It was considered a balanced and sinusoidal three-phase voltage at the PCC given by equations (15)-(17).

$$u_{an}(t) = 127\sqrt{2}\sin(120\pi t)\ [V] \quad (15)$$

$$u_{bn}(t) = 127\sqrt{2}\sin\left(120\pi t - \frac{2\pi}{3}\right)\ [V] \quad (16)$$

$$u_{cn}(t) = 127\sqrt{2}\sin\left(120\pi t + \frac{2\pi}{3}\right)\ [V] \quad (17)$$

- The total DC bus voltage (u_{dc}) is set to 480V.
- The frequency and the amplitude of the triangular carrier are set to 10 kHz and $u_{dc}/\sqrt{3}$, respectively.
- The sampling frequency is set to 10 kHz for the PI and Deadbeat controllers and 20 kHz for Delta Modulation [9].
- The coupling inductance was set to 50mH in order to obtain a low ripple in the injected current.
- The proportional gain and the integral time of the PI controller were set to 3000 and 0,000385, respectively.

B. *Comparison criteria*

The criteria used to evaluate comparatively the three current control techniques were the maximum steady state error and the effective error of the current generated by the inverter, as shown in equations (18) and (19), respectively, for $k = \{a, b, c, d\}$.

$$\Delta I_{max} = \max\left(i_{refk}(t) - i_k(t)\right) \quad (18)$$

$$\Delta I_k = \sqrt{\frac{1}{T}\int_t^{t+T}\left(i_{refk}(t) - i_k(t)\right)^2} \quad (19)$$

C. *Results*

Case I: Unbalanced and distorted currents

The reference tracking for case I by using Delta Modulation, the PI regulator and the Deadbeat controller are shown in figures (4), (5) and (6), respectively. These figures present the reference currents and the injected currents for phases *a*,*b* and *c*.

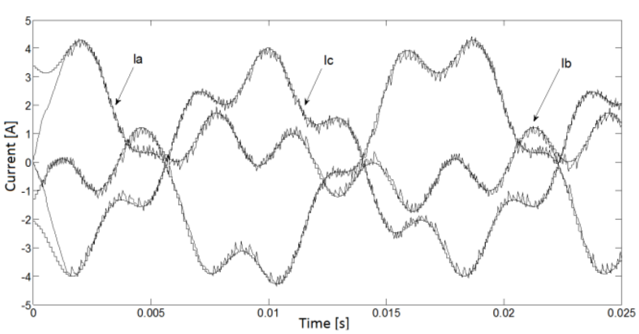

Fig. 4. Case I: Tracking by Delta Modulation

Also, table I presents the maximum steady state error and the maximum effective error obtained in the tracking of these reference currents.

As can be seen, the best reference tracking is obtained using the Deadbeat controller. Also, the reference tracking made by the PI regulator has the highest current variations of the three techniques.

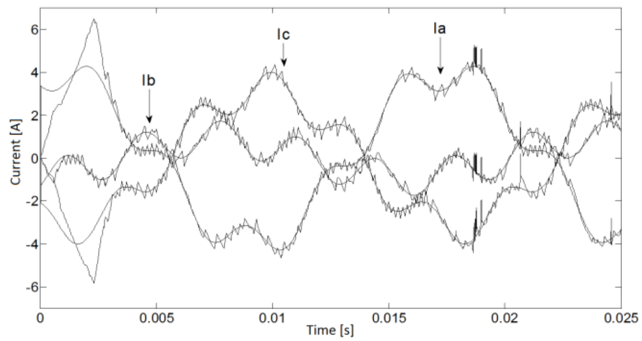

Fig. 5. Case I: Tracking by PI regulator

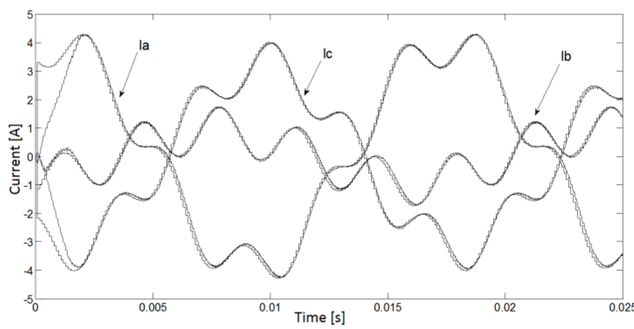

Fig. 6. Case I: Tracking by Deadbeat controller

TABLE I
SIMULATION RESULTS

	Dead Beat		*Delta Modulation*		*PI*	
	Case I	*Case II*	*Case I*	*Case II*	*Case I*	*Case II*
ΔI[A]	0,1647	0,0881	0,1754	0,1356	0,189	0,1837
ΔImax[A]	0,4882	0,1686	0,5579	0,3638	0,773	1,0704

Case II: Unbalanced currents with homopolar sequence components

The results of the reference tracking for phases *a*,*b* and *c* are shown in figures (7), (8) and (9) by using Delta Modulation, the PI regulator and the Deadbeat controller, respectively. The reference current and the injected current for leg *d* are presented in figures (10), (11) and (12). Also, in Table I are shown the maximum errors for this case.

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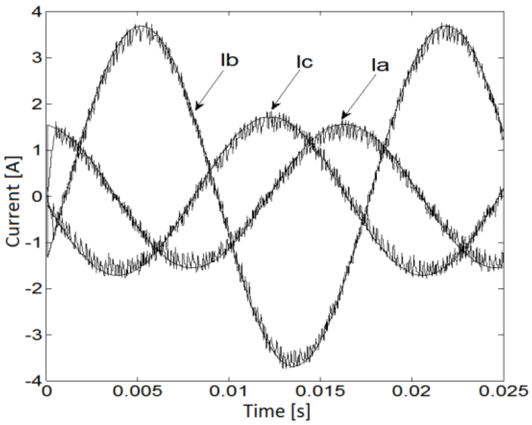

Fig. 7. Case II: Tracking by Delta Modulation

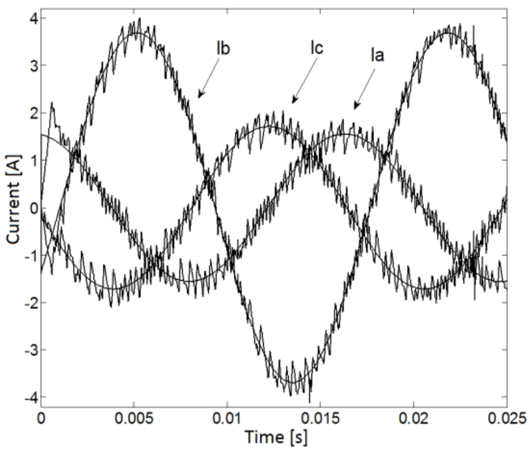

Fig. 8. Case II: Tracking by PI regulator

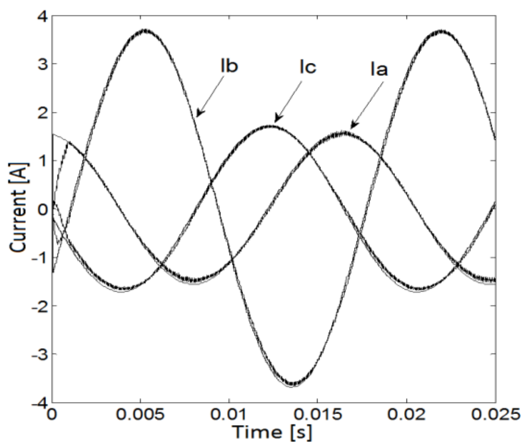

Fig. 9. Case II: Tracking by Deadbeat controller

Figures (7)-(12) and the results presented in table I show the outstanding performance of the three controllers and the FLFB-VSI topology in the tracking of currents with homopolar sequence components. Figures (10), (11) and (12) show that the current injected by the *d*-leg corresponds to the homopolar sequence component.

As seen in Table I, the Deadbeat controller offers the lowest tracking error of the three techniques. In addition, the PI regulator presents the highest current ripple.

The results shows that this topology allows the injection of unbalanced references with homopolar sequence components and it can be used for shunt active power filters applications when the injection of this kind of currents is required.

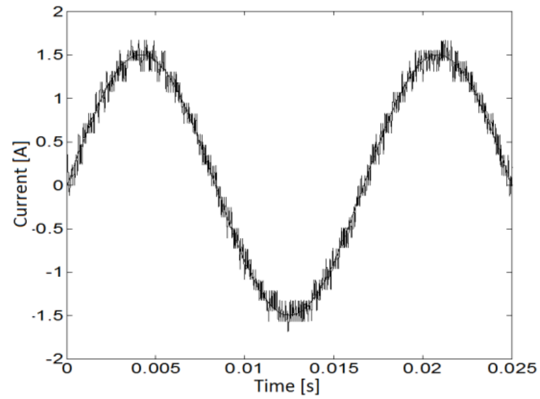

Fig. 10. Case II: Tracking in d-leg by Delta Modulation

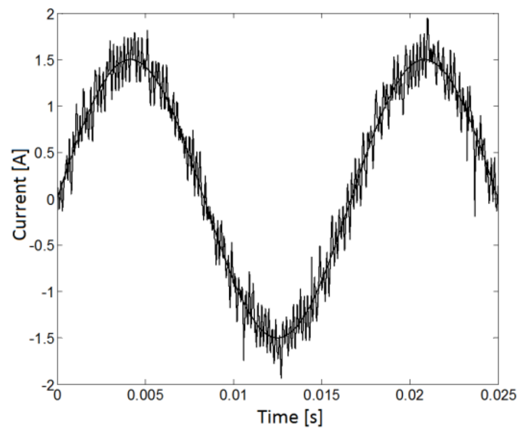

Fig. 11. Case II: Tracking in d-leg by PI regulator

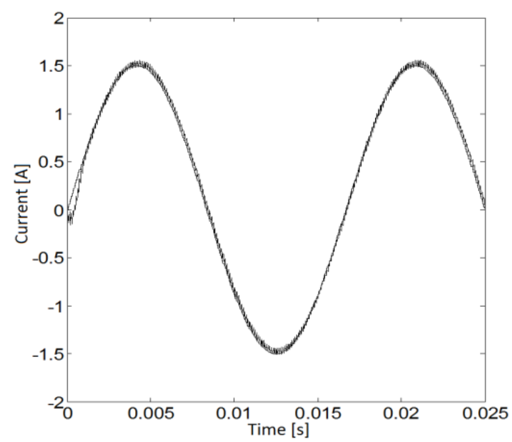

Fig. 12. Case II: Tracking in d-leg by Deadbeat controller

The small errors obtained by using the Deadbeat controller show that it is a good option to follow this kind of references. Furthermore, according to table I the errors obtained in case II are smaller than those obtained in case I. Therefore, it can be concluded that this topology presents a better tracking when it is considered the injection of nonzero homopolar sequence currents.

VI. Conclusions

In this paper, it was presented a comparative analysis between the Delta Modulation, the PI regulator and the Deadbeat controller used to obtain the firing pulses of the FLFB-VSI topology in the tracking of unbalanced and distorted current references including homopolar sequence components. According to the results, the three algorithms present a good performance when they follow distorted and unbalanced currents with and without homopolar sequence components. In this way, the results show that these controllers and the analyzed topology are a good choice for shunt active power filters applications when the injection of this kind of currents is required.

In conclusion, the Deadbeat controller presents the lowest tracking error and the best performance of the three analyzed controllers for the FLFB-VSI topology. This good performance can be due to the fact that it is based on the parameters of the system. In addition, the Delta Modulation showed good results in the simulations. This controller is the simplest of the three algorithms and it does not require high processing effort.

VII. Acknowledgment

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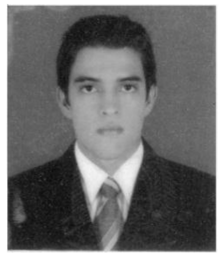

Juan Rueda was born in San Gil (Santander), Colombia, 1989. He received the B.Sc degree in electrical engineering from the Universidad Industrial de Santander (UIS), Bucaramanga, Colombia, in 2013. His areas of interest include: power quality, power electronics and active power filters.

Ernesto Pieruccini was born in San Gil (Santander), Colombia, 1988. He received the B.Sc degree in electrical engineering from the Universidad Industrial de Santander (UIS), Bucaramanga, Colombia, in 2013. His areas of interest include: power quality, power electronics and active power filters.

María Mantilla was born in Bucaramanga (Santander), Colombia, 1985. She received the B.Sc. and M.Sc. degrees in electronic engineering from the Universidad Industrial de Santander (UIS), Bucaramanga, Colombia, in 2008 and 2011, respectively. She is currently pursuing the PhD degree in electronic engineering at the UIS. She is a Professor at the Universidad Industrial de Santander (UIS-Colombia) and a researcher at the Grupo de Investigación en Sistemas de Energía Eléctrica (GISEL). Her areas of interest include: power quality, power electronics, photovoltaic systems, control systems and signal processing.

Johann Petit was born in Villanueva (La Guajira), Colombia. He received the B.Sc. and M.Sc. degrees in electrical engineering from the Universidad Industrial de Santander (UIS), Bucaramanga, Colombia, in 1997 and 2000, respectively. He received his PhD in Electrical Engineering from the Universidad Carlos III de Madrid (UC3M), Spain, in 2007. Currently, he is a Professor at the Universidad Industrial de Santander (UIS-Colombia) and a researcher at the Grupo de Investigación en Sistemas de Energía Eléctrica (GISEL). His areas of interest include: power quality, power electronics and signal processing algorithm for electrical power systems.