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Four-branch Star Hybrid Power Filter for Three-phase Four-wire Systems

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***Abstract*- This paper presents a new concept for filtering current harmonics in three-phase four-wire networks. The four-branch star (FBS) filtering topology presented in this work is characterized by a particular layout consisting of single-phase inductances and capacitors. Via this layout, a power filter, with two different and simultaneous resonance frequencies and sequences, is achieved –one frequency for positive-/negative-sequence and another one for zero-sequence components. This filter topology can work either as a passive filter or as a hybrid filter. The paper analyzes the proposed topology and derives fundamental concepts about the control of the resulting hybrid power filter. From this analysis, a specific implementation of a three-phase four-wire hybrid power filter is presented as an illustrative application of the filtering topology. An extensive evaluation using simulation and experimental results is conducted in order to verify and validate the good performance of the proposed four-branch star passive/hybrid power filter.**

I. INTRODUCTION

The importance of the problem originated by current harmonics in terms of power quality, reliability and continuity of supply, mainly at low-voltage (LV) levels, is evidenced by the international standards limiting current harmonics injection into the grid [1]-[3]. Current harmonics in LV distribution grids mostly results from the widespread usage of nonlinear loads. At medium voltage (MV) level, currents harmonics are mainly due to singular loads such as furnace ovens and big frequency line rectifiers. Three-phase three-wire loads generate positive-/negative-sequence (pn-seq) current harmonics. These harmonics give rise to resonances, voltage distortion, over-heating, losses increasing, etc. On the other hand, single-phase nonlinear loads are usually connected between the phase and neutral conductors and additionally originate zero-sequence (z-seq) current harmonics –typically with 3rd, 9th and 15th harmonic order. These z-seq harmonics are summed up in the neutral conductor and, as well as causing characteristic problems related to pn-seq harmonic currents, give rise to neutral conductor overload, common-mode neutral to earth voltages, increasing of phase voltage distortion and transformers overheating [4].

As a solution to the current harmonics, the shunt connected current power filters can be classified as:

- *Shunt LC resonant passive power filters* (SPPF) [5][6]. These shunt filters are designed to offer a very low impedance path to current harmonics at the tuning frequency. Main advantages of the SPPF are their simplicity and low cost. However, their filtering characteristic strongly depends on the grid impedance. Tuning frequency of the SPPF is also modified by parameters tolerance and components ageing. Additionally, the SPPFs consume reactive current at the fundamental frequency, generating additional losses, and can result in parallel/series resonances.
- *Shunt active power filters* (SAPF) [7]. These filters are based on a power converter working as a current source in closed-loop mode. The SAPF are able to cancel out load currents harmonics and unbalance, resulting in perfectly balanced sinusoidal currents at the source side. However, their cost is still relatively high, which slows down their massive application in distribution networks.
- *Shunt hybrid power filters* (SHPF) [8-10]. These filters result from the combination of the passive and active power filters. The SHPF exhibit a fairly good filtering characteristic, which is almost independent of the grid impedance. Moreover, thanks the low power rate of the power converter, the cost of a SHPF is substantially lower than in the case of a SAPF.

SPPF are usually constituted by simple resonant cells, with a single resonance frequency. Therefore, it is necessary installing as many individual LC filters as characteristic current harmonics should to be cancelled out. SPPF are not typically applied to cancel the 3rd order current harmonic, the highest among the z-seq current harmonics. If a SPPF was tuned at the 3rd harmonic, the resonance frequency of the LC resonant cell would be very close to the fundamental frequency, typically 50/60 Hz. As a consequence, the current absorbed by the filter at the fundamental frequency, for a reasonable quality factor, would be around the current drained at the 3rd harmonic, which would make this filtering solution economically unviable.

This paper presents a new concept for filtering current harmonics in three-phase four-wire networks. The proposed filter is based on a four-branch star (FBS) filtering topology characterized by a particular layout of single-phase inductors and capacitors, without using any transformer or special electromagnetic device. Via this layout, the FBS power filter offers two different and simultaneous resonance frequencies and sequences, i.e., one frequency for pn-seq and another one for z-seq components. The FBS filter topology can work either in passive mode, when only passive components are

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employed, or in hybrid mode, when a power converter is integrated into the FBS structure to improve its performance.

In the following, the FBS topology is introduced and some of its most interesting variants are highlighted. A three-phase four-wire hybrid power filter is chosen as a preferred implementation of the FBS topology, being analyzed and evaluated by both simulations and experiments.

II. The FBS Power Filter Topology

The FBS filter has four individual star-connected passive branches, three phase-branches and one neutral-branch. A FBS shunt power filter together the three-phase grid which the filter is connected to are shown in Fig. 1. Three identical single-phase impedances Z_f are connected in the phase-branches whereas a fourth single-phase impedance Z_n is connected in the neutral-branch. The FBS power filter is connected to a generic three-phase network in which pn-seq voltage components, $\mathbf{u}_{12}=[u_{ao},u_{bo},u_{co}]$, and z-seq voltage components, u_0, have been represented separately in Fig. 1 for for the sake of clarifying the superposition analysis presented in the following.

In the first analysis step, only pn-seq components are considered in the circuit of Fig. 1. Therefore, it is assumed u_0 = 0, which means the center nodes at the source and filter sides (o-o') are virtually connected and hence $v_{oo'}$ = 0. Therefore, the pn-seq impedance of the FBS power filter $\vec{Z}_{12}$ at a particular frequency is given by the following quotient of phasors:

$$\vec{Z}_{12}=\frac{\vec{U}_{12}}{\vec{I}_{12}}=\frac{\vec{U}_{fo}}{\vec{I}_{f}}=\frac{\vec{U}_{fo'}}{\vec{I}_{f}}=\vec{Z}_{f} \quad \text{with} \quad f=\{a,b,c\}, \tag{1}$$

being $\vec{U}_{12}$ and $\vec{I}_{12}$ the pn-seq voltage and current phasors affecting to the FBS power filter, respectively.

In the second analysis step, only the z-seq component is considered in the circuit of Fig. 1. If assumed that $\mathbf{u}_{12}=0$, the z-seq impedance of the FBS power filter, $\vec{Z}_0$, at a certain frequency is given by:

$$\vec{Z}_{0}=\frac{\vec{U}_{0}}{\vec{I}_{0}}=3\frac{\vec{U}_{on}}{\vec{I}_{n}}=\frac{\vec{U}_{o'n}}{\vec{I}_{n}}\frac{\vec{Z}_{f}+3\vec{Z}_{n}}{\vec{Z}_{n}}=\vec{Z}_{f}+3\vec{Z}_{n}, \tag{2}$$

where $\vec{U}_0$ and $\vec{I}_0$ are the z-seq voltage and current phasors affecting to the FBS filter, respectively.

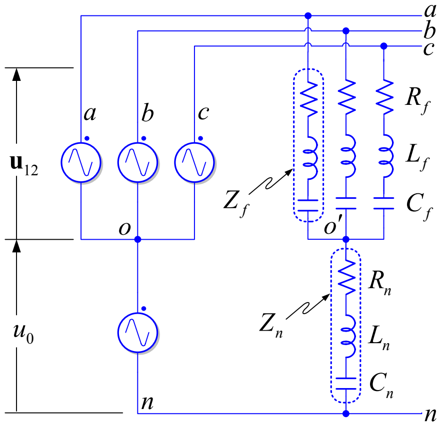

Fig. 1. FBS power filter based on simple series LC resonant cells.

Single-phase impedances constituting the FBS power filter are resonant cells. These resonant cells could be as complex as necessary. However, a reasonably good filtering characteristic is obtained in practice when such resonant cells are built by simple series LC resonant circuits as shown in Fig. 1, presenting a single resonance frequency. The phase and neutral impedances of the filter of Fig. 1, Z_f and Z_n respectively, are given by:

$$\vec{Z}_{f}=R_{f}+j\left(L_{f}\omega-\frac{1}{C_{f}\omega}\right);\ \vec{Z}_{n}=R_{n}+j\left(L_{n}\omega-\frac{1}{C_{n}\omega}\right). \tag{3}$$

Connection of the LC resonant cells according to the FBS topology gives rise to two groups of resonance frequencies, i.e., one group for the pn-seq components and another one for the z-seq components. This means that the shunt passive power filter with FBS topology is able to perform selective filtering of current harmonics by means of setting up low impedance paths to particular currents components with specific frequencies and sequences. In the FBS filter of Fig. 1, both the pn-seq impedance, $\vec{Z}_{12}$, and the z-seq impedance, $\vec{Z}_0$, can be calculated by substituting impedances of (3) into (1) and (2), that is:

$$\vec{Z}_{12}=R_{f}+j\left(L_{f}\omega-\frac{1}{C_{f}\omega}\right), \tag{4}$$

$$\vec{Z}_{0}=\left(R_{f}+3R_{n}\right)+j\left[\left(L_{f}+3L_{n}\right)\omega-\frac{1}{\omega}\left(\frac{1}{C_{f}}+\frac{3}{C_{n}}\right)\right]. \tag{5}$$

Impedance of (4) and (5) evidence that the FBS filter of Fig. 1 presents two resonance frequencies, namely one for the pn-seq components, f_{12}, and another one for the z-seq components, f_0. These frequencies are given by:

$$f_{12}=\frac{1}{2\pi}\frac{1}{\sqrt{L_{f}C_{f}}}, \tag{6}$$

$$f_{0}=\frac{1}{2\pi}\frac{1}{\sqrt{\left(L_{f}+3L_{n}\right)\left(\frac{C_{f}C_{n}}{C_{n}+3C_{f}}\right)}}. \tag{7}$$

These two resonance frequencies are totally independent. It is a useful characteristic in the case when the z-seq resonance frequency is set near to the fundamental grid frequency, e.g., f_0=150Hz for a 50Hz grid. Under such operating conditions, the z-seq circuit would absorb no current at fundamental frequency for a balanced grid voltage. As previously mentioned, the FBS power filter provides these filtering characteristics without using either transformers or special electromagnetic devices, which results in lower cost and higher modularity than in other existing commercial solutions.

The FBS filter admits several variants by modifying the generic network of Fig. 1. As shown in Fig. 2, one of these

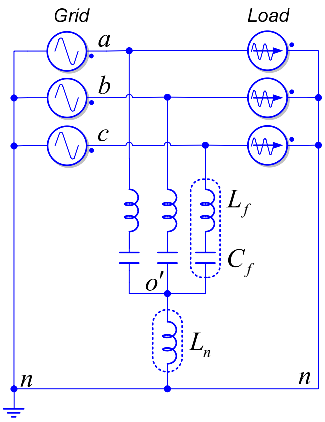

Fig. 2. FBS power filter suitable for applications where $f_0 < f_{12}$.

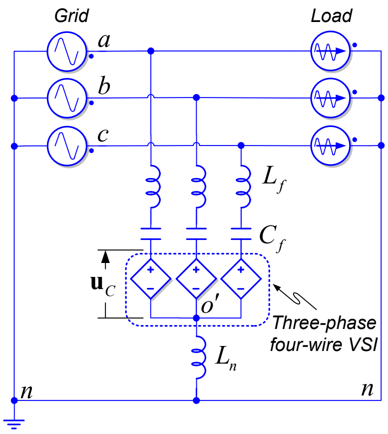

Fig. 3. Specific implementation of a three-phase FBS hybrid power filter.

variants consists in a particular configuration of the FBS passive power filter suitable for those applications where the z-seq resonance frequency, f_0, is lower than the pn-seq resonance frequency, f_{12}. In this FBS implementation, the phase-branch impedances are constituted by series LC resonant cells and the neutral-branch impedance only consists of a single-phase inductance, L_n. Resistances R_f and R_n have been intentionally omitted in Fig. 2 since they are not of interest for calculating the resonance frequencies. These resonance frequencies are given by:

$$f_{12} = \frac{1}{2\pi}\frac{1}{\sqrt{L_f\,C_f}}, \tag{8}$$

$$f_0 = \frac{1}{2\pi}\frac{1}{\sqrt{\left(L_f + 3L_n\right)C_f}}. \tag{9}$$

The FBS filter of Fig. 2 is very simple; however the resonant cells of the phases and neutral branches could be constituted by more complex networks to obtain multiple resonance frequencies using only one FBS power filter [6].

III. The FBS Hybrid Power Filter

Even though the FBS power filter presented in §II offers good performance in cancelling out current harmonics in three-phase four-wire systems under optimal operating conditions, its filtering characteristic however is affected by typical problems of any passive filter, i.e., its filtering capability depends on the value of the grid impedance, there exists risk of resonance, retuning is necessary due to ageing and tolerances.

A solution to overcome drawbacks associated to passive filters consists in integrating a power converter into the filter structure. This filtering system is known as a hybrid power filters [11]. A properly designed and well controlled power converter can generate any voltage-current relationship at its output, obviously provided that it works inside its operative range. Therefore, such power converter could be understood as a 'virtual impedance' integrated into the original structure of the passive filter. This virtual impedance improves the behaviour of the original passive filter by increasing its capability for draining off current harmonics at frequencies different from the resonance ones, compensating drifts in the passive filter parameters, and damping oscillations due to resonance phenomena.

Fig. 3 shows a specific implementation of a three-phase four-wire FBS hybrid power filter integrating a four-terminal VSI into its structure. This VSI can simultaneously synthesize both pn-seq and z-seq voltages at its output, which makes it suitable for improving both the pn-seq and the z-seq passive filter characteristics at the same time. Therefore, a proper control of the FBS hybrid power filter shown in Fig. 3 can make it an effective solution for cancelling out the most characteristic pn-seq current harmonics, i.e., the 5th, 7th, and 11th order harmonics, together the z-seq 3rd order current harmonic.

It should be highlighted that the power converter of the FBS hybrid power filter is much smaller and inexpensive than the power converter of a conventional active power filter. This is mainly due to the fact that the power converter of the FBS hybrid power filter is exclusively devoted to generate those necessary harmonic voltages to inject the desired harmonic currents into the grid. The grid voltage at fundamental frequency drops across the capacitors of the LC resonant cells and so it should not be provided by the power converter. Hence, the dc-link voltage of the power converter in a FBS hybrid power filter can be significantly reduced in relation to the conventional shunt active power filter –around 90% lower [12].

IV. Control of the FBS Hybrid Power Filter

The control algorithm of the FBS filter proposed in this work is very simple and it can be schematically depicted by de diagram of Fig. 4(a). In this diagram, $\mathbf{u}_C$ represents the voltage at the output of the VSI; Z_S is the grid impedance; Z_F is the impedance of the FBS network for both pn-seq and z-seq, which is given by:

$$\vec{Z}_F = \vec{Z}_{12} = R_f + j\left(L_f\omega + \frac{1}{C_f\omega}\right) \text{ or}$$
$$\vec{Z}_F = \vec{Z}_0 = \left(R_f + 3R_n\right) + j\left[\left(L_f + 3L_n\right)\omega - \frac{1}{C_f\omega}\right]; \tag{10}$$

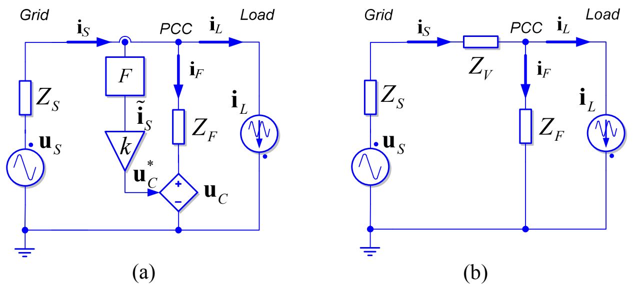

Fig. 4. (a) Simple control diagram of the FBS hybrid power filter, (b) Equivalent circuit with a virtual impedance resulting form the control law.

the block F represents a filter in charge of extracting those individual frequencies suitable to be filtered ($\tilde{\mathbf{i}}_S$) from the grid current ($\mathbf{i}_S$) and k is the gain of the proportional controller generating the reference voltage for the VSI ($\mathbf{u}_i^*$).

The resonant cells of the FBS hybrid power filter of Fig. 3 offers very low impedance to pn-seq and z-seq currents at the tuning frequencies f_{12} and f_0, respectively. Therefore, a low dc-link voltage –only about 10% of the grid voltage, is necessary in the VSI to inject into the grid significant levels of harmonic currents at the frequencies f_{12} and f_0. However, impedance offered by the resonant circuits grows as frequency goes far away from the resonance ones. As a positive consequence, the current ripple injected by the FBS hybrid power filter into the grid at the switching frequency is very low. However, this also implies that the FBS hybrid power filter only can compensate a limited range of the pn-seq and z-seq current harmonics. For this reason, a filtering block (F) is necessary to extract those individual harmonics to be cancelled, which will be near of the resonance frequencies of the FBS network. As aforementioned, the reference voltage of the VSI is obtained by using a simple proportional regulator with gain k. The control law of the equivalent control diagram shown in Fig. 4(a) is given by:

$$\mathbf{u}_C^* = Z_V \cdot \mathbf{i}_S \quad ; \quad Z_V = \mu \cdot k \cdot F\,, \tag{10}$$

where μ is the gain of the VSI. A straightforward analysis of the diagram shown in Fig. 4(a) conducts to the following transfer function:

$$\mathbf{i}_S = \frac{1}{Z_F + Z_S + Z_V}\left(\mathbf{i}_L Z_F + \mathbf{u}_S\right). \tag{11}$$

Transfer function of (11) reveals that integration of a VSI controlled by the control law of (10) into the FBS hybrid filter structure is equivalent to inserting a virtual impedance Z_V upstream of the point of common coupling (PCC) between the hybrid power filter and the grid. Fig. 4(b) shows the resultant equivalent circuit including the virtual impedance Z_V. This virtual impedance increases the capability of the hybrid power filter for cancelling out the load-side harmonics, isolates the hybrid power filter from the grid-side current harmonics and reduces the risk of resonances between the resonant cells and the grid impedance [13]. The control law proposed in this work is intentionally simple; however it can be improved by implementing an enhanced controller consisting of individual regulators with a different gain for each of the current harmonics to be compensated [14][15].

V. Performances of the FBS Hybrid Power Filter

A preferred implementation of the three-phase four-wire FBS hybrid power filter is shown in Fig. 5. To evaluate the performance of the proposed hybrid power filter, three single-phase diode rectifiers injecting current harmonics at the load-side ($\mathbf{i}_L$) are considered. In this particular implementation, a conventional three-leg full-bridge VSI with the negative rail of the dc-bus connected to the neutral conductor is used for injecting both pn-seq and z-seq currents into the three-phase four-wire grid. This interesting VSI connection, patented in [16], was applied in [17] to a conventional three-phase four-wire hybrid power filter with only one common resonance frequency for both the positive-/negative- and the z-seq components. In that work however, a too high and costly dc-link voltage had to be used for controlling the current injected into the grid (500Vdc for 400Vac mains). The FBS hybrid power filter presented in this paper overcomes this drawback thanks to its two independent resonance frequencies –one for pn-seq and another one for z-seq components, which allows controlling currents with both sequences using a low dc-link voltage level (about 50Vdc for 400Vac mains).

The output voltage of the VSI of Fig. 5, referenced to the negative dc-bus rail, is formed by both ac and dc components. The dc component is blocked by the C_f capacitors and thus it does not inject any dc current into the grid. The ac component of the VSI output voltage has a maximum span of $\pm u_{dc}/2$ and is in charge of injecting pn-seq and z-seq current into the grid in order to cancel out the grid current harmonics. Therefore, the gain of the VSI of Fig. 5 is given by $\mu = u_{dc}/2$.

Fig. 6 shows the simple control system designed to drive the three-phase four-wire FBS hybrid filter of Fig. 5. Three fourth-order notch filters (NF), one per phase, with a center frequency of 50Hz and a bandwidth of 5Hz extract the current harmonics $\tilde{\mathbf{i}}_S$ to be compensated. A proportional per phase regulator with gain k=2.5 controls the harmonic current injected into the grid. The dc-link voltage control is performed by a PI regulator with a rather low bandwidth

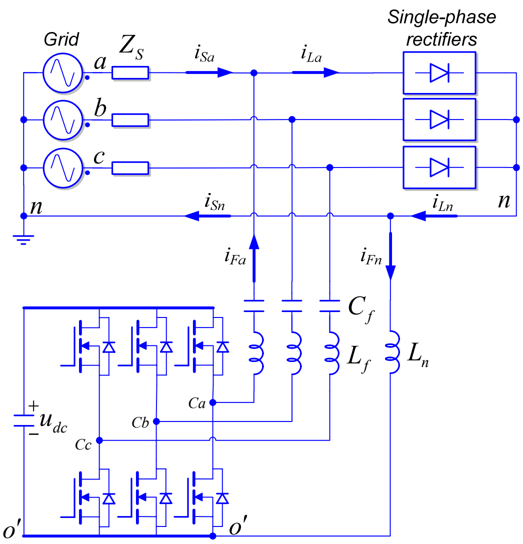

Fig. 5 Practicable implementation of a three-phase FBS hybrid power filter.

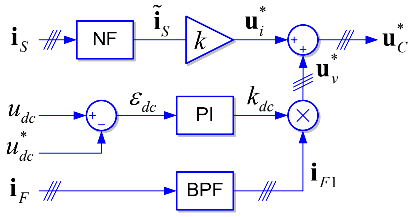

Fig. 6. Control of the three-phase FBS hybrid power filter.

(k_p=10, τ_i=1s). This regulator sets a proportionality coefficient k_{dc} between the fundamental frequency current flowing through the FBS filter $\mathbf{i}_{F1}$ and the fundamental frequency voltage at the output of the VSI. A fourth-order band-pass filter (BPF) with a center frequency of 50Hz and a bandwidth of 5Hz is used to extract the current $\mathbf{i}_{F1}$.

To evaluate the effectiveness of the proposed FBS power filter, its connection to a grid with parameters of Table I was considered in simulation.

TABLE I
GRID PARAMETERS USED IN SIMULATION

Nominal power	Line Voltage	Line resistance (1.5%)	Line inductance (6.25%)
10kW	400V/50Hz	240mΩ	3,2mH

The three single-phase rectifiers of Fig. 5 consume 2.5kW, demand a phase current i_{La} with a rms value of 4.1A (THD=43.5%), and inject an almost 3rd-harmonic sinusoidal current in the neutral conductor with a rms value of 4.9A. Table II shows the main parameters of the three-phase four-wire FBS power filter. Applying (8) and (9) to this set of parameters, resonance frequencies for the pn-seq and z-seq components are f_{12}=300Hz and f_0= 150Hz, respectively. Capacitive reactive power supplied by the resonant cells is Q_F=1.64kvar for a 400V/50Hz grid.

TABLE II
PARAMETERS OF THE FBS HYBRID POWER FILTER

Parameter	Value
Filter phase-branch inductance (L_f)	8.5mH
Filter phase-branch resistance (R_f)	244mΩ
Filter phase-branch capacitance (C_f)	33.5µF
Filter neutral-branch inductance (L_n)	8.5mH
Filter neutral-branch resistance (R_n)	244mΩ
Nominal dc-link voltage (U_{dc})	45V
Dc-link capacitor (C_{dc})	14100µF
Switching frequency (f_{SW})	14.4kHz

The FBS hybrid filter of Fig. 5 is evaluated under two different operation modes, namely the passive and the hybrid modes. In the passive mode, the $\mathbf{i}_S$ input of the control system of Fig. 6 is forced to zero and hence the reference voltage $\mathbf{u}_i^*$ is zero as well. Hence, the VSI does not contribute to the filtering action. The virtual impedance Z_V of (11) should be considered equal zero in the passive mode. In the hybrid mode, the FBS power filter controller of Fig. 6 provides the proper reference voltage $\mathbf{u}_i^*$ to the VSI in order to cancel out pn-seq and z-seq current harmonics at the grid-side.

Some simulation results are shown in Fig. 7. The FBS filter works in the passive mode until t=0.44s; then the active mode starts. The Figs. 7(a) and 7(b) show the currents in the phase a and in the neutral conductor respectively. In the passive mode, the FBS filter should be draining off the z-seq 3rd-harmonic and attenuating the pn-seq 5th- and 7th-harmonics since f_0=150Hz and f_{12}=300Hz. However, Fig. 7(a) shows that the 5th-harmonic is not attenuated but amplified at the source-side as a consequence of a parallel resonance phenomenon occurred between the FBS power filter and the grid impedance.

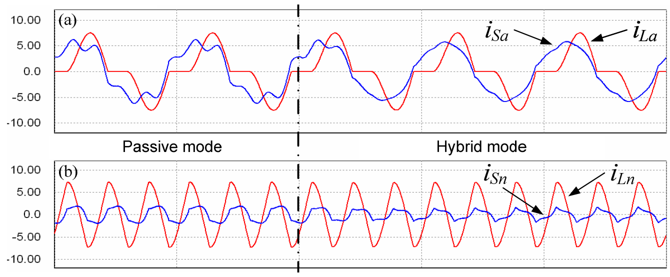

Fig. 7. Simulation results for the three-phase four-wire FBS hybrid power filter. (a) phase currents, (b) neutral currents.

Based on (11), Fig. 8 shows the frequency response of the FBS power filter in the presence of both z-seq and pn-seq current harmonics at the load-side. The relationship between i_S and i_L when the FBS filter works in the passive mode is represented by dashed lines. Two resonance peaks are identified in the passive mode, one for z-seq components at 141Hz and another one for pn-seq components at 254Hz. This second peak justifies the high level of 5th-harmonic in i_S when the resonance phenomenon is excited by the 5th-harmonic current injected by the load-side rectifiers. The FBS filter works in the hybrid mode from t=0.44s and its filtering characteristic is improved. The resonance at the 5th-harmonic is cancelled and the harmonic content in the grid current is reduced further. Once steady state conditions are reached in the hybrid mode, the phase current i_{Sa} has a THD of 7.3% and

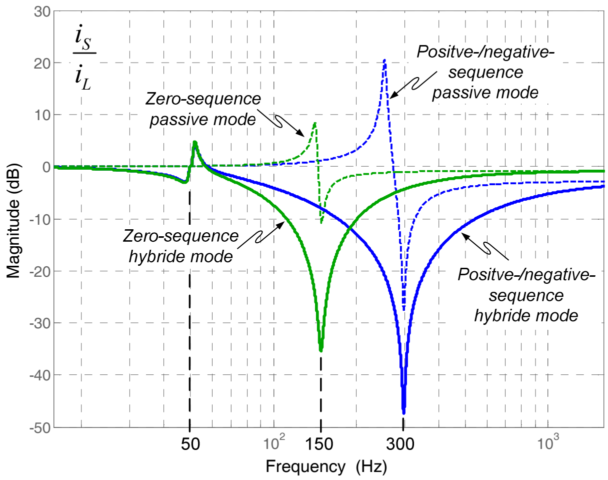

Fig. 8. Frequency response of the three-phase four-wire FBS power filter.

the neutral current i_{Sn} has a rms value of 0.75A. The frequency response of the FBS filter when working in hybrid mode, represented by solid lines in Fig. 8, shows that the resonance peaks are cancelled out and the bandwidth of both the pn-seq and the z-seq filtering characteristics is enlarged.

VI. EXPERIMENTAL RESULTS

Performances of the three-phase four-wire FBS hybrid power filter were evaluated by using an experimental prototype. MOSFET devices IRF540N 100V/33A were used to implement the single-phase VSI of Fig. 5. The light control algorithm of Fig. 6 was programmed into a low-cost 16-bit fixed-point DSP dsPIC30F6010 running at 30MIPS. Parameters for the grid, power filter and loads in the experimental test-bed matched to those used in simulation and listed in Tables I, II.

Fig. 9 shows representative records of measured currents in the experimental prototype. In these scopes, a dash-dot line indicates the transition time from the passive to the hybrid operating mode. Figs. 9(a) and 9(b) respectively show current in the phase *a* and in the neutral conductor. These waveforms are fairly similar to those obtained by simulation and shown in Fig. 7. However, the current distortion due to the parallel resonance between the FBS filter and the grid at the fifth harmonic was even higher in the experimental setup than in simulation. The neutral current i_{sn} presented similar levels to those obtained in simulation and the small difference could be due to both tolerances in the filter components and precision errors in the control algorithm.

VII. CONCLUSION

A new filter concept, the four-branch star (FBS) topology was presented in this paper. Analysis, simulations and experiments conducted in this paper proved the FBS power filter topology as an effective and economical solution for current conditioning in three-phase four-wire networks. Connection of resonant cells according to FBS topology results in independent low impedance paths for both pn- and z-seq components at specific frequencies, which allows performing selective filtering of current harmonics in both the phases and the neutral conductor of a three-phase four-wire system. The FBS power filter topology can operate in either passive or hybrid mode. In this second mode, a very simple VSI –with a dc-link voltage around 10% of the grid line voltage, extends further filtering capability of the passive network as well as it avoids overloads and unexpected resonances.

A simple three-phase VSI and a light control algorithm were used in this work to emphasize economy and simplicity of the proposed filtering solution. Simulation and experimental results confirmed the good behavior of the proposed filtering solution in canceling out current harmonics in both the phase and the neutral conductor.

ACKNOWLEDGMENT

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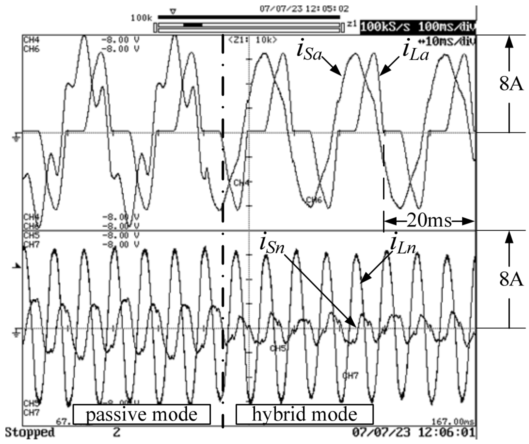

Fig. 9. Experimental results for the three-phase four-wire FBS hybrid power filter. (a) phase currents, (b) neutral currents.

REFERENCES

[1] IEEE Std. 519-1992: *IEEE Recommended practices and requirements for harmonic control in electrical power systems*. IEEE, 1992.

[2] Electromagnetic Compatibility (EMC), Part 3: Limits, Section 2: *Limits for harmonics current emissions (equipment input current <16A per phase)*, IEC-61000-3-2, 1997.

[3] Electromagnetic Compatibility (EMC), Part 3: Limits, Section 4: *Limitation of emissions of harmonics currents in low-voltage power supply systems for equipment with rated currents greater than 16A*, IEC-61000-3-4, 1998.

[4] R. C. Dugan, M. F. McGranaghan, S. Santoso, and H. W, Beaty, *Electrical Power Systems Quality*, 2nd edition, New York: McGraw Hill, 2002.

[5] J. C. Das, "Passive filters – potentialities and limitations," *IEEE Trans. Ind. App.*, vol. 40, pp. 232-241, Jan./Feb. 2004.

[6] J. Arrillaga, D. A. Bradley, and P. S. Bodger, *Power System Harmonics*. pp. 304-306, New York: Wiley, 1985.

[7] B. Sing, K- A´-Haddad, and A. Chandra, "A review of active filters for power quality improvement," *IEEE Trans. Ind. Electron.*, vol. 46, pp. 960-971, Oct. 1999.

[8] R. Inzunza and H. Akagi, "A 6.6-kV transformerless shunt hybrid active filter for installation on a power distribution system," *IEEE Trans. on Power Electron.*, vol.20, pp. 893- 900, Jul. 2005.

[9] S. Bhattacharya, D. Divan, and P. Cheng, "Hybrid solutions for improving passive filter performance in high power applications," *IEEE Trans. Ind. Applicat.*, vol. 33, pp. 732–747, May/June 1997.

[10] H. Akagi, S. Srianthumrong, and Y. Tamai, "Comparisons in circuit configuration and filtering performance between hybrid and pure shunt active filters," *in Proc. IEEE Industry Applications Soc. Conf.*, 2003, pp. 1195–1202.

[11] D. Rivas, L. Moran, J.W. Dixon, and J.R. Espinoza, "Improving passive filter compensation performance with active techniques," *IEEE Trans. Ind. Electron.*, vol.50, pp. 161-170, Feb 2003.

[12] L. Asiminoaei, W. Wiechowski, F. Blaabjerg, B. Kedra, and T. Krzeszowiak, "A new control structure for hybrid power filter to reduce the inverter power rating", *in Proc. IEEE Ind. Electron. Conf. (IECON'06)*, 2006, pp. 2712-2717.

[13] H. Fujita, T. Yamasaki, and H. Akagi, "A hybrid active filter for damping of harmonic resonance in industrial power systems," *IEEE Trans. Power Electron.*, vol.15, pp.215-222, Mar 2000.

[14] D. Basic, V.S. Ramsden, and P.K. Muttik, "Harmonic filtering of high-power 12-pulse rectifier loads with a selective hybrid filter system," *IEEE Trans. Ind. Electron.* , vol.48, pp.1118-1127, Dec 2001.

[15] M. Liserre, R. Teodorescu, F. Blaabjerg, "Multiple harmonics control for three-phase grid converter systems with the use of PI-RES current controller in a rotating frame," *IEEE Trans. Power Electron.*, vol. 21, pp. 836-841, May 2006.

[16] M. Lamich, J. Balcells, J. Garcia, D. Gonzalez, and J. Gago, "New structure for three phase four wires hybrid active filters," *in Proc. IEEE Ind. Electron. Conf. (IECON'06)*, 2006, pp. 1603-1608.