ACTIVE SERIES FILTER UNDER DISTORTED AND UNBALANCED OPERATION CONDITIONS: PROBLEM OR SOLUTION

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Abstract – **This paper discusses the performance of a combined system consisting of two small rating series active filters based on synchronous reference frame controller and a shunt passive filter for a three-phase four- wire power system under unbalanced conditions. The active series filters have been shown an ideal solution for realizing a harmonic free utility interface when it operates under balanced conditions. However the power system imbalance affects the accuracy of the active series filters once the SRF controller is not able to detect the zero sequence components and by the poor effectiveness of passive filter under the imbalance, making it unable to operate properly. It's demonstrated by simulation using Matlab/Simulink.**

Keywords - **Active Filters, Synchronous Reference Frame, Imbalance, Zero sequence Components.**

I. INTROTUCTION

Currently, the papers proposed to the Active Series Filters based on Synchronous Reference Frame Controllers established analysis focusing just the balanced operating conditions and three-phase three-wire systems [1]-[3]. However, the three-phase four-wire distribution systems have been widely employed to deliver electric power at low voltage levels. With the changing on the operating conditions in recent years due the rapid growth of advanced power conversion devices, and added to the naturally distribution power system imbalance, the zero sequence harmonic currents accumulate in the neutral conductor which is used to zero sequence components to keep flowing through the phases.

Apart of it, the synchronous reference frame (SRF) controllers are not able to detect all the harmonics components present in the phase conductors under unbalanced conditions, once the zero sequence components in the SRF are ignored.

Series/shunt active filters for three-phase four-wire distribution systems have already been presented [4], [5], [6], but none of them were developed in SRF base.

In this paper, the real limitations about the Active Series Filters based on SRF method in unbalanced systems are demonstrated for a three-phase four-wire system. It's done with a combine system composed by two series active filters and a shunt passive filter. By simulation, it is implemented and investigated, emphasizing that the SRF controller is a limited method to mitigate harmonics currents in unbalanced systems.

II. COMBINE SYSTEM PRICIPLE OF OPERATION

The harmonic mitigation is achieved by the harmonic isolation between load and source through an active impedance, *K1*, which ideally presents zero impedance (short-circuit) at fundamental frequency and a high resistance (open-circuit) at harmonic frequencies. This active impedance is implemented by the source harmonic current detection using a synchronous reference frame (SRF) controller. It's put on the system like voltage, *Vaf1*, compensating the source harmonic voltage, thus blocking the flow of harmonic currents from the supply into the passive filters and the flow of load harmonic currents into the source, being dry by the passive filter.

According to references [1], [2] and [3], the command of instantaneous ac voltage of active series filter FAS1, *Vaf1* is given by:

$$Vaf1 = k1 \cdot Ish \tag{1}$$

Here *Ish* is the harmonic current in the supply, and *K1* is a gain which has dimensions in ohms. It should be noted that the resistance *K1* is identical to the gain *K1*. If *K1* is infinite under an ideal control conditions, the source harmonic current, *Ish* , the ac voltage of active filter, *Vaf1*, and the load bus harmonic voltage, *Vbrr*, are:

$$Ish = 0 \tag{2}$$

$$Vbrr = -\left(Zfh \cdot Ilh\right) \tag{3}$$

$$Vaf1 = Vsh + \left(Zfh \cdot Ilh\right) \tag{4}$$

It's clear that the power rating of FAS1 is depended by the voltage drop across the passive filter, *Zfh*ILh*, and by the source harmonic voltage, *Vsh*.

Lets assume *Vsh* = 0. To decrease the rating of the series active filter FAS1, the harmonic voltage across the shunt passive filter has to be minimized. However if *ILh* contains harmonic components having unspecified frequencies other than tuned frequencies in passive filter, a relatively large amount of harmonic voltage would occur on this the bus.

To avoid the overload on the FAS1 a second active filter, FAS2, is inserted in series with the passive filter. The FAS2 has the ability to cancel the harmonic voltage which appears due the non-negligible impedance of passive filter PF, thus providing a low impedance branch of harmonic currents.

The command of instantaneous ac voltage of active series filter FAS2, *Vaf2* is given by:

$$Vaf2 = -k2 \cdot Vfh \tag{5}$$

Here, *K2* is a unity gain under an ideal control conditions and *Vfh* is a harmonic voltage existing in the terminal voltage across the passive filter.

Now *Ish*, *Vbrr* and *Vaf2* are given by:

$$Ish = Vsh/Zsh \tag{6}$$

$$Vbrr = 0 \tag{7}$$

$$Vaf2 = Vsh \cdot (Zf/Zs) + Zfh \cdot Ilh \tag{8}$$

The features of the active series filters under balanced condition can be found in [3], [7] and [8].

III. IMBALANCE AND HARMONIC DISTORTION

In case of imbalance, the odd harmonics does not adhere to the sequence component theory, which has been established for the representation of harmonics considering a balanced system and balanced operation condition. However, symmetrical components theory can be applied to individual harmonics. Each harmonic can be decomposed into sequence components and individually be transformed to its zero, positive and negative sequence components respectively using equation 9.

$$\begin{bmatrix} I_0 \\ I_+ \\ I_- \end{bmatrix} = \frac{1}{3} \begin{bmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{bmatrix} \cdot \begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix} : a = 1\angle 120^0 \tag{9}$$

Whenever unbalance occurs in a system the three phase currents are unequal in magnitude and displaced from each other by angles other than 120 degrees. Therefore, they do not add up to zero (phasor addition) and have a finite value of current flowing through the neutral. As soon as the degree of unbalance increases, the magnitude of non-characteristics harmonics goes on increasing. This is accompanied by a corresponding decrease in magnitude of the characteristic harmonic [9].

When the 6-pulse converter operates under balanced conditions it's observed that the characteristics harmonics current produced by the converter are of the order $6n \pm 1 \quad n = 1,2,3\ldots$. If the power system has any sort of unbalance, non-characteristics harmonics appear.

In this work, the imbalance is achieved by having a single-phase load at the converter bus. The single-phase load and also the three-phase load are converters voltage load type.

IV. DESIGN OF SHUNT PASSIVE FILTER

The combined filter system can improve the characteristic of shunt passive filter, and eliminate the series and parallel resonance. These advantages make it easy to design the shunt passive filter used with the series active filter, compared with that used alone.

Design of passive filters for harmonic filtering often results in significant fundamental reactive power and unacceptable leading DPF when the load is a VSI type. In the other way different to this, the resulting THD voltage across the passive filter may be extremely high.

The AC line reactors help to reduce the supply current THD and allow effectiveness' implementation of passive filters reaching acceptable DPF with smaller THD voltage across the passive filters, what contributes to reduce the required power rating of series active filters. To optimize the designing of *Zf* helps to lead good results [10].

The shunt passive filters, SPF, used in this work consist of 5^{th} and 7^{th} tuned RLC filter, isolated eye, 76KVA.
The parameters are specified in table 1.

Table I
Circuit Constants of Passive Filter

Order	Indutance	Capacitance	Qr
5^{th}	1.5mH	188uF	100
7^{th}	1.5mH	96uF	100

V. SYNCHRONOUS REFERENCE FRAME CONTROLLER

The system controllers used for the active series filter and the completely description of the controller can be found in [11]. The controller uses a negative sequence SRF based controller to extract fundamental negative sequence load current.

This ensures that the series active filters does not compensate for fundamental negative sequence current in the supply/load and performs only its intended function of harmonic isolation. Consequently, the SRF controlled active filter inverter does not require an increased rating to supply the fundamental (60Hz) imbalance of three-phase system and it also prevents overloading of active series filters in the presence of imbalance.

Under unbalanced conditions the LPF cutoff frequency, *fc*, has to be as small as possible. Unfortunately, transient performance deteriorates if *fc* is very small. To use a high order LPF helps effectively to reach a better transient characteristic, but the system becomes unstable when *K* is too large [12]. To avoid a poor compensation characteristic and the instability of the system due the imbalance, the dynamics features of the system has to be investigated.

For the system studied, 3-phase 4-wires, the zero sequence harmonics components are not nil. However, in the Park's transformation only the positive and negative sequence harmonics components are changed in frequency [13].

Rewriting the output voltage of FAS1, *Vaf1*, it can be conclude that the active impedance is created by the superposition of each harmonic component detected in the source current.

$$Vaf1 = k1 \cdot \sum_{h=2}^{\infty} Ish(h) \tag{10}$$

Assuming that each harmonic included in the source current has its ideal infinite harmonic impedance that isolate it from the source, not to detect any harmonic means does not isolate it from the source.

$$Vaf1 = k1 \cdot \left[\sum_{h=2}^{\infty} Ish_{pos}(h) + \sum_{h=2}^{\infty} Ish_{neg}(h) + \sum_{h=2}^{\infty} Ish_{zero}(h) \right] \quad (11)$$

As the SRF controller does not detect the zero sequence component of the source harmonic current, the FAS1 presents zero impedance to the zero sequence harmonics components.

Being unable to improve the harmonic resistance to zero sequence harmonic components they will keep flowing through the system.

In the same way, the FAS2 is controlled, except by FAS1 be controlled as a current controlled harmonic voltage source while FAS2 is controlled by voltage.

VI. ACTIVE SERIES FILTER IMPLEMENTATION

The figure 1 shows the power system configuration and a circuit diagram of the combined system.

The power system and the distribution system are represented by their equivalent system [14]. The utility 4160V/480V transformer is rated 750KVA with 1.3% impedance (30.75mΩ and 35.5uH) referred to 480V and 58MVA base. The Short Circuit Ratio (SCR) at the utility transformer is 12.3 based on an average load current of 656A. The utility short circuit capacity is 58MVA and the short circuit fault current is 8059A. The three-phase and the single-phase loads are rated 310KVA and 15.5KVA respectively, with input ac side line reactors (0.1mH).

The active series filters consist of six full bridges single-phase voltage source PWM inverter, which are independently controlled focusing to compensate the unbalanced harmonics. The gains K1 and K2 were decided by simulation and set to 5 and 0.8 respectively.

VII. SYSTEM BEHAVIOR WITH FPP, FAS1 AND FAS2

The degree of unbalance used in the study is set to 5%, $(Iseq - / Iseq +)$, achieved by unequal load distribution, previously explained . The figures 2.a to 2.f show the load harmonic current and the neutral current with their respectively harmonic amplitude spectrum.

The imbalance of the load current can be proved by the neutral current flow and also by the non-characteristics harmonics in the load current.

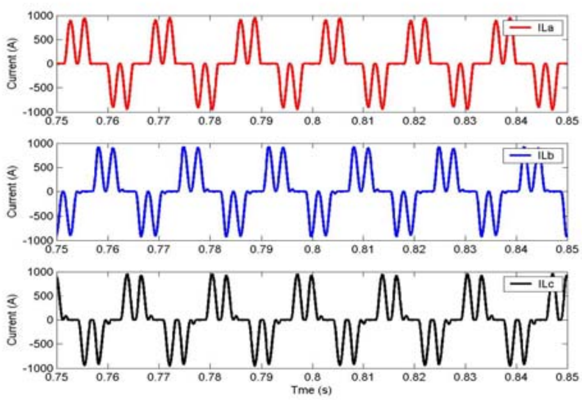


Fig. 2a. Load Current

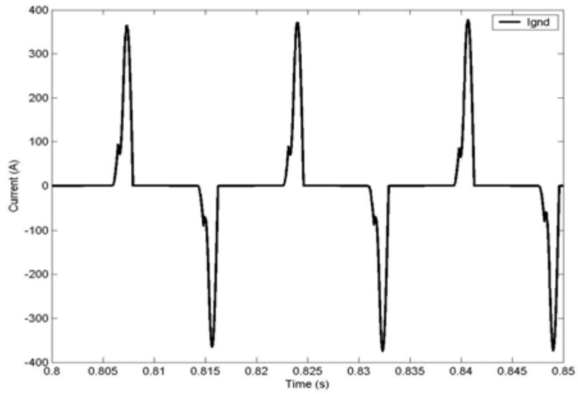


Fig. 2b. Neutral Current

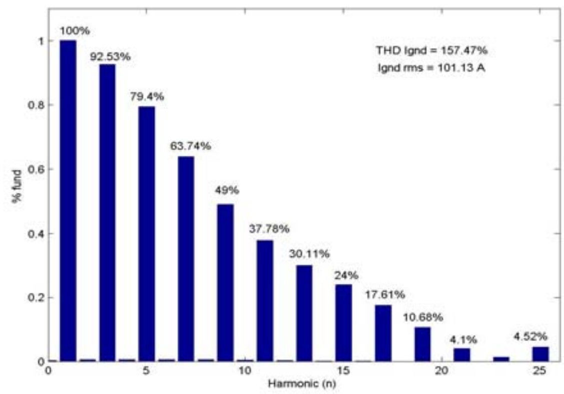


Fig. 2c. Neutral Current Spectrum

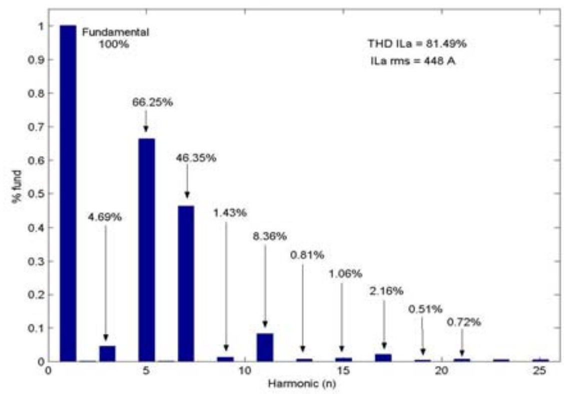


Fig. 2d. Ph A Load Current Spectrum

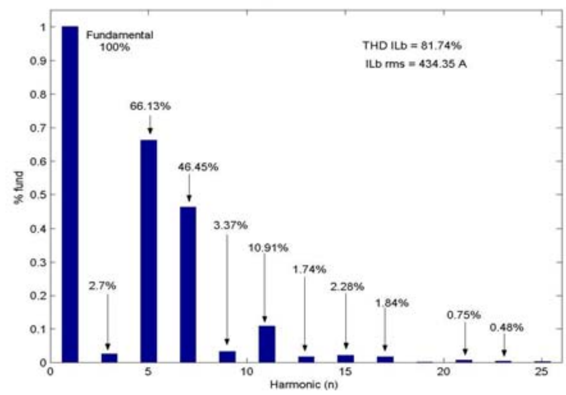


Fig. 2e. Ph B Load Current Spectrum

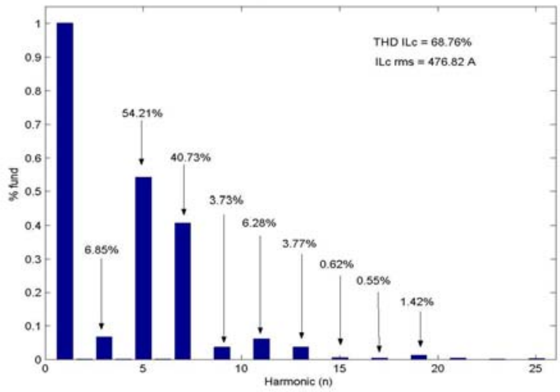


Fig. 2f. Ph C Load Current Spectrum

The amount of harmonic current dried by the passive filter is also unbalanced, resulting in unbalanced load bus voltage. Here, the imbalance load bus voltage measured was 1.7%. The figure 3 gives evidence against the phenomenon.

Aforesaid in section IV, the DPF keeps a little leading as shown in figure 4. As a result the THD load bus voltage is still high, 6%, 5.5% and 5.9% for the phases A, B, C respectively.

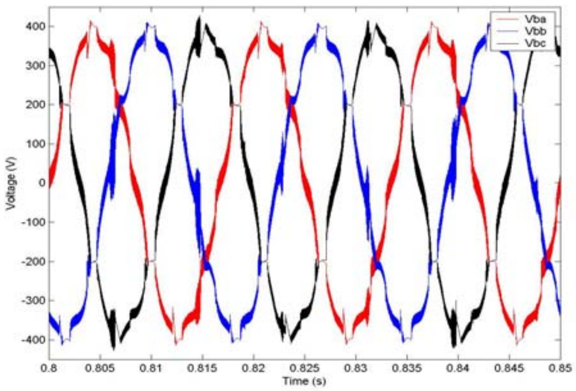


Fig. 3. Load Bus Voltage

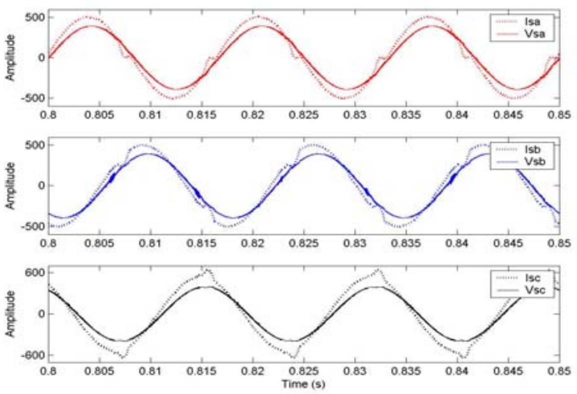


Fig 4. Is and Vs Displacement

Due the flowing of positive and negative harmonics sequence components which are used to the SRF controller to create the FAS reference signal, an increase rating is required by the FAS proportional to the unbalance. As the dc link voltage of the inverters is limited to a finite value the ever increasing of unbalance will lead the FAS to the saturation, once the unbalance determines the amplitude of the non-characteristic harmonics.

Figures 5a and 5b exhibit the output voltages of the FAS1 and FAS2 to the unbalanced system. Table 2 exhibits the rms output voltage values of the actives filter FAS1 and FAS2 under the balanced and unbalanced conditions.

The SRF controller does not detect the zero sequence component of the source harmonic current. With no harmonic isolation to zero sequence harmonic components it keeps flowing through the system like the fundamental frequency does. It can be seen in the figures 6.a to 6.d.

Even with the FAS insertion, the source line current exceed the upper harmonics limits recommended by IEEE 519 Standard, which establish 5% THD for current and voltage to a SCR smaller than 20.

Here, only the current THD didn't follow the rule, having a THD of 8.17%, 8.15% and 7.04% for the phases A, B and C respectively.

Note that for any sort of imbalance on the system, since the way of flow to the zero sequence components doesn't exist, the SRF will be able to detect all the harmonics components, even the odd non-characteristics harmonic.

Applying the Symmetrical components theory to each load harmonic current and comparing it with the values given by the FFT's source harmonic currents, concludes that the residual harmonics components in the source current are, essentially, the zero sequence harmonics components of the load harmonic current which were not isolated. Table 3 brings the values.

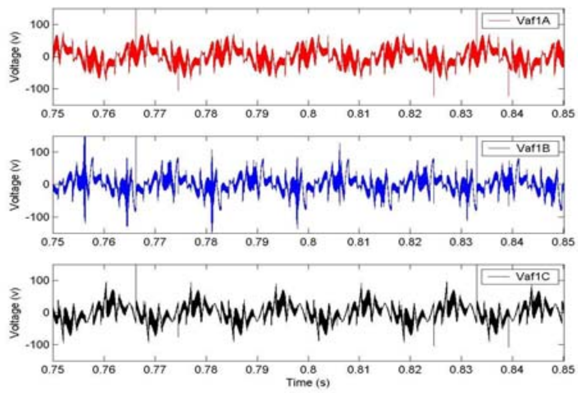


Fig. 5a Output Voltage FAS1

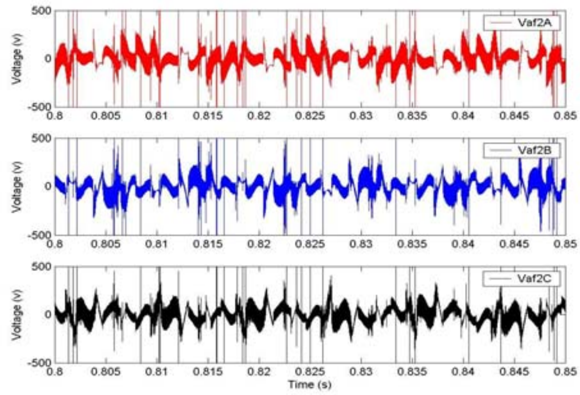
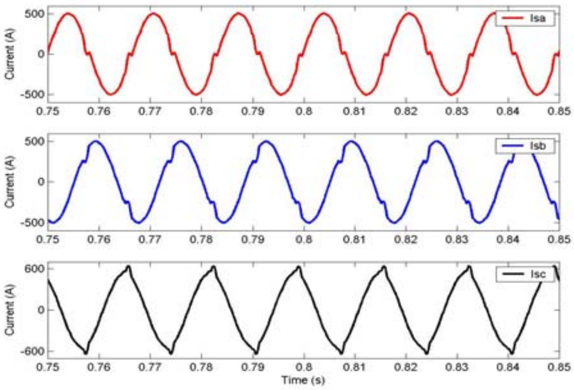


Fig. 5b. Output Voltage FAS2



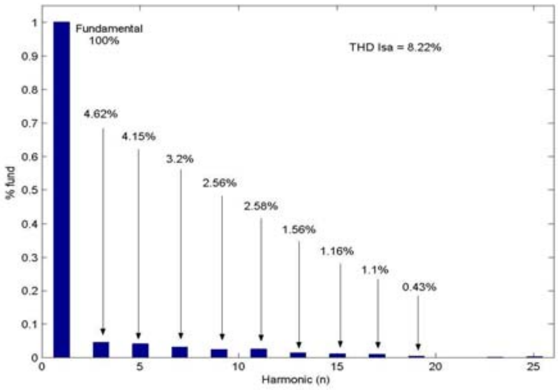


Fig. 6b. Ph A Source Current Spectrum

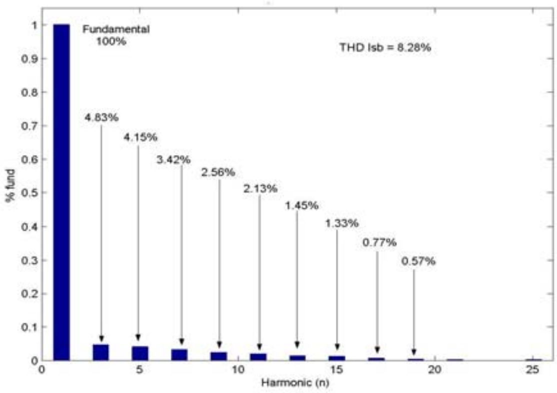


Fig. 6c. Ph B Source Current Spectrum

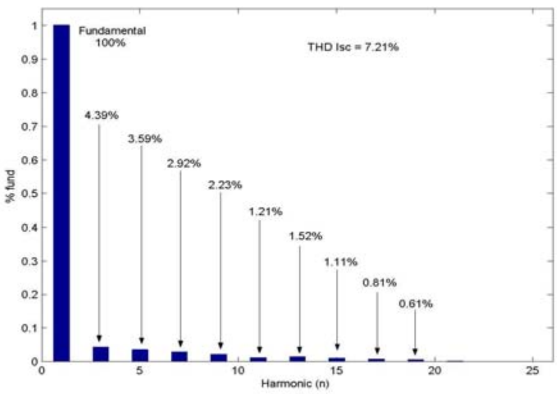


Fig. 6d. Ph C Source Current Spectrum

Table II
Active Filters Voltage

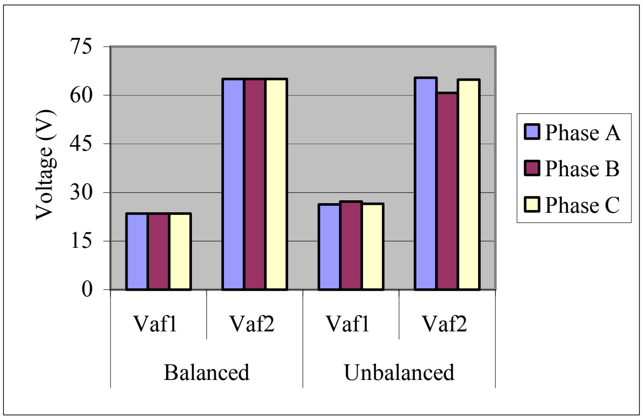
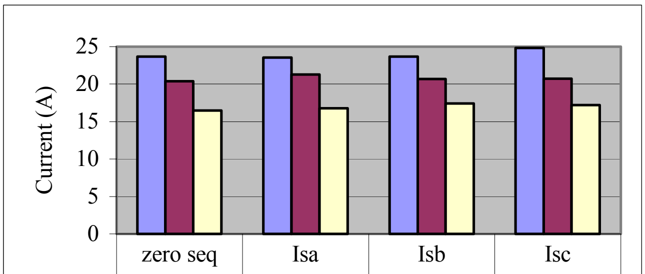


Table III
Zero Sequence Current Values



	zero seq	Isa	Isb	Isc
3	23,7	23,55	23,68	24,85
5	20,4	21,31	20,69	20,73
7	16,5	16,77	17,4	17,2

VII. CONCLUSION

Under the Power Quality point of view, the active series filter is extremely attractive. However, for unbalanced systems the Combined System has a sort of limitation that must be emphasized:

1) The zero sequence harmonics components are not compensated due the limitations in the controller methodology, improved in synchronous reference frame.
2) An increase power rating of the FAS and overload of the passive filter occurs.
3) Impossibility of having simultaneously unity displacement power factor and low voltage distortion on the load bus to VSI load type.
4) The harmonics limits recommended by IEEE 519 Standard are violated even with active filtering.
5) The THD load bus voltage remains high.

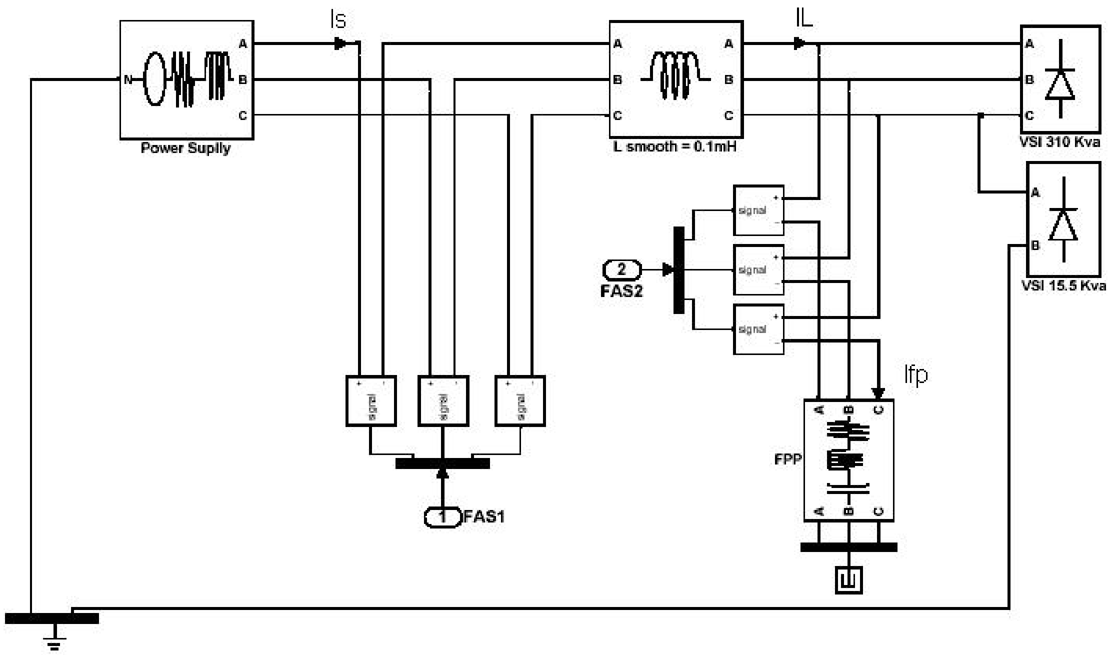


Fig. 1. System Implementation of Active Series Filters and Shunt Passive Filters.

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