International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 2 Issue 11, November - 2013

Enhancement of Electric Power Quality by Using Hybrid Power Filters

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Abstract—* The growing interest in power quality has lead to a variety of devices designed for mitigating power disturbances such as harmonics caused due to different problems. By minimizing the total harmonic distortion the harmonic pollution in the power system will be reduced and power quality will be increased. A control algorithm for a three-phase hybrid power filter is proposed. Power quality standards (IEEE-519) compel to limit the total harmonic distortion within the acceptable range. Active power filter which has been used there monitors the load current constantly and continuously adapt to the changes in load harmonics. Hybrid active filter with proposed control algorithm for three phase hybrid power filter is studied here .It is composed of series active filter connected in series to the line and passive filter connected in parallel with the load. Traditionally, a passive LC power filter is used to eliminate source current harmonics when it is connected in parallel with the load and series active filter will compensate the voltages in the line. The proposed control algorithm is based on the generalized p–q theory. It can be applied to both harmonic voltage injection and harmonic current injection and also it improves the behavior of the passive filter. This control algorithm is also applied to shunt active power filter, combination of series active and shunt active and comparative study has been done. Simulations have been carried out on the MATLAB SIMULINK platform with different filters and results are presented..

***Index Terms*—Active power filters, harmonics, hybrid filters, instantaneous reactive power, power quality.**

I. INTRODUCTION

A power-quality problem is an occurrence manifested in a nonstandard voltage, current, or frequency deviation that results in a failure or a disoperation’s of end-use equipment. Power quality is a reliability issue driven by end users. There are three concerns. The characteristics of the utility power supply can have a detrimental effect on the performance of industrial equipment. Both distorted current and voltage may cause end-user equipment to malfunction, conductors to overheat and may reduce the efficiency and life expectancy of the equipment connected at the PCC. Traditionally, a passive LC power filter is used to eliminate current harmonics when it is connected in parallel with the load [1]. This compensation equipment has some drawbacks [2]–[4], due to which the passive filter cannot provide a complete solution. These disadvantages are mainly the following.

—The compensation characteristics heavily depend on the system impedance because the filter impedance has to be smaller than the source impedance in order to eliminate source current harmonics.

—Overloads can happen in the passive filter due to the circulation of harmonics coming from nonlinear loads connected near the connection point of the passive filter.

—They are not suitable for variable loads, since, on one hand, they are designed for a specific reactive power, and on the other hand, the variation of the load impedance can detune the filter.

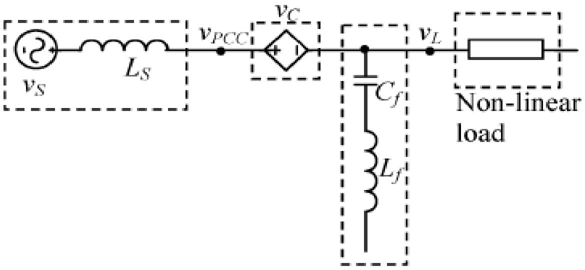


Fig 1. Series Active filter and Passive shunt filter

—Series and/or parallel resonances with the rest of the System can appear. An active power filter, APF, typically consists of a three phase pulse width modulation (PWM) voltage source inverter [5]. When this equipment is connected in series to the ac source impedance it is possible to improve the compensation characteristics of the passive filters in parallel connection [6], [7]. This topology is shown in Fig. 1, where the active filter is represented by a controlled source, where is the voltage that the inverter should generate to achieve the objective of the proposed control algorithm. Different techniques have been applied to obtain a control signal for the active filter [8]–[10]. One such is the generation of a voltage proportional to the source current harmonics [11], [12].With this control algorithm, the elimination of series and/or parallel resonances with the rest of the system is possible. However, at the limit this would be an infinite value and would mean that the control objective was impossible to achieve. The chosen k value is usually small so as to avoid high power active filters and instabilities in the system. However, the choice of the appropriate k value is an unsolved question since it is related to the passive filter and the source impedance values. Besides, this strategy is not suitable for use in systems with variable loads because the passive filter reactive power is constant, and therefore, the set compensation equipment and load has a variable power factor. In another proposed control technique, the APF generates a voltage waveform similar to the voltage harmonics at the load side but in opposition [13]. This strategy only prevents the parallel passive filter depending on the source impedance; the other limitations of the passive filter nevertheless remain.

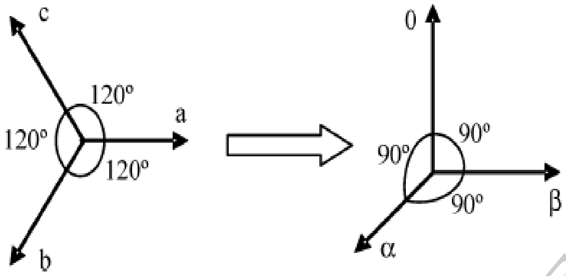


Fig. 2. Transformation from the phase reference system (abc) to the οαβ system.

Other control strategies combining both the above have been proposed to improve the parallel passive filter compensation characteristics [12], [13], but they continue to suffer from the difficulty of finding an appropriate value for the APF gain k. Finally, another approach has recently been proposed [16]. It suggests that the active filter generates a voltage which compensates the passive filter and load reactive power, so it allows the current harmonics to be eliminated. The calculation algorithm is based on the instantaneous reactive power theory [11]. There, the control target is to achieve constant power in the source side. In this paper a new control strategy based on the dual formulation of the electric power vectorial theory [11], [10] is proposed. For this, a balanced and resistive load is considered as reference load. The strategy obtains the voltage that the active filter has to generate to attain the objective of achieving ideal behavior for the set hybrid filter-load. When the source voltages are sinusoidal and balanced the power factor is unity, in other words, the load reactive power is compensated and the source current harmonics are eliminated. By this means, it is possible to improve the passive filter compensation characteristics without depending on the system impedance, since the set load-filter would present resistive behavior. It also avoids the danger that the passive filter behaves as a harmonic drain of close loads and likewise the risk of possible series and/or parallel resonances with the rest of the system. In addition, the compensation is also possible with variable loads, not affecting the possible the passive filter detuning. Although the APF series control based on the instantaneous reactive power theory is not new, in this paper the authors propose a new formulation that has consequences in the control loop design. In fact, the instantaneous reactive power here is defined from a dot product whereas in [9], [13] it is defined as a cross product; this results in a remarkable simplification in the Implementation of the reference generation method. The final development allows any compensation strategy to be obtained, among them, unit power factor. The compensated electric system was simulated in MATLAB-Simulink, and the strategy was applied to a three-phase system with balanced and unbalanced loads. The simulation results used to verify the theoretical behavior are presented. Finally, an experimental prototype was manufactured and its behavior checked. Experimental results are also presented.

II. THE DUAL INSTANTANEOUS REACTIVE POWER THEORY

The instantaneous reactive power theory is the most widely used as a control strategy for the APF. It is mainly applied to compensation equipment in parallel connection.

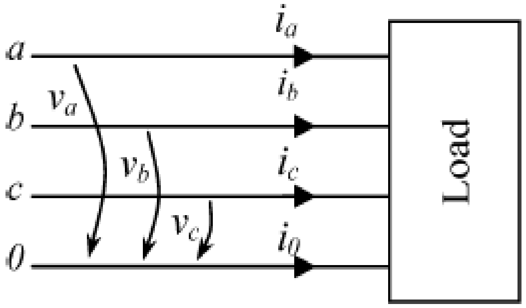


Fig. 3. Three-phase system

This theory is based on a Clarke coordinate transformation from the phase coordinates (see Fig. 2). In a three-phase system such as that presented in Fig. 3, Voltage and current vectors can be defined by

$$v = [v_a \quad v_b \quad v_c]^T \quad i = [i_a \quad i_b \quad i_c]^T. \tag{1}$$

The vector transformations from the phase reference system a-b-c to οαβ coordinates can be obtained, thus

$$\begin{bmatrix} v_0 \\ v_\alpha \\ v_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1/\sqrt{2} & 1/\sqrt{2} & 1/\sqrt{2} \\ 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix} \begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} \quad (2)$$

$$\begin{bmatrix} i_0 \\ i_\alpha \\ i_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1/\sqrt{2} & 1/\sqrt{2} & 1/\sqrt{2} \\ 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix}. \quad (3)$$

The instantaneous real power in the frame is calculated as follows:

$$p_{3\phi}(t) = v_\alpha i_\alpha + v_\beta i_\beta + v_0 i_0. \quad (4)$$

This power can be written as

$$p_{3\phi}(t) = p + p_0. \quad (5)$$

where is the instantaneous real power without zero sequence component and given by

$$p = v_\alpha i_\alpha + v_\beta i_\beta. \quad (6)$$

It can be written in vectorial form by means of dot product

$$p = \boldsymbol{i}_{\alpha\beta}^{T} \boldsymbol{v}_{\alpha\beta} \quad (7)$$

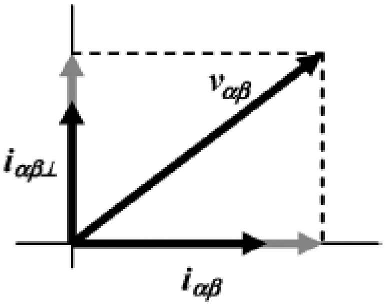


Fig. 4. Decomposition of the voltage vector.

In the plane, and vectors establish two coordinates axes. The voltage vector can be decomposed in its orthogonal projection on the axis defined by the currents vectors, Fig. 4. By means of the current vectors and the real and imaginary instantaneous power, the voltage vector can be calculated

$$\boldsymbol{v}_{\alpha\beta} = \frac{p}{i_{\alpha\beta}^2} \boldsymbol{i}_{\alpha\beta} + \frac{q}{i_{\alpha\beta}^2} \boldsymbol{i}_{\alpha\beta\perp} \quad (8)$$

In a four-wire system, the zero sequence instantaneous power, Po, is not null. In this case, (15) would have to include an additional term with the form (P_o/i_o^2) Io, where i_o is the zero sequence current vector.

III. COMPENSATION STRATEGY

Electric companies try to generate electrical power as sinusoidal and balanced voltages so it has been obtained as a reference condition in the supply. Due to this fact, the compensation target is based on an ideal reference load which must be resistive, balanced and linear. It means that the source currents are collinear to the supply voltages and the system will have unity power factor. If, in Fig. 3, voltages are considered as balanced and sinusoidal, ideal currents will be proportional to the supply voltages.

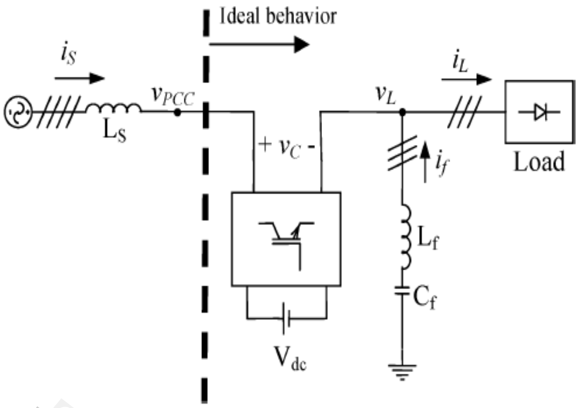


Fig. 5. System with compensation equipment.

The average power supplied by the source will be

$$P_S = I_1^2 R_e. \quad (9)$$

In this equation, is the square rms value of the fundamental harmonics of the source current vector. It must be supposed that when voltage is sinusoidal and balanced, only the current fundamental component transports the power consumed by the load. Compensator instantaneous power is the difference between the total real instantaneous power required by the load and the instantaneous power supplied by the source

$$p_C(t) = p_L(t) - p_S(t). \quad (10)$$

Fig. 5 shows the system with series active filter, parallel passive filter and unbalanced and non sinusoidal load. The aim is that the set compensation equipment and load has an ideal behavior from the PCC. The voltage at the active filter connection point in coordinates can be calculated as follows:

$$\boldsymbol{v}_{PCC\alpha\beta} = \frac{P_L}{I_1^2} \boldsymbol{i}_{\alpha\beta} \quad (11)$$

$$\boldsymbol{v}_{C\alpha\beta}^{*} = \left(\frac{P_L}{I_1^2} - \frac{p_L}{i_{\alpha\beta}^2} \right) \boldsymbol{i}_{\alpha\beta} - \frac{q_L}{i_{\alpha\beta}^2} \boldsymbol{i}_{\alpha\beta\perp} \quad (12)$$

When the active filter supplies this compensation voltage, the set load and compensation equipment behaves as a resistor. Finally, if currents are unbalanced and non sinusoidal, a balanced resistive load is considered as ideal reference load. Therefore, the equivalent resistance must be defined by the equation. Reference signals are obtained by means of the reference calculator shown in Fig. 9 and Fig. 10. In the case of unbalanced loads, the block "fundamental component calculation" in Fig. 9 is replaced by the scheme shown in Fig. 17, which calculates the current positive sequence fundamental component. The compensation target imposed on a four-wire system is the one presented in (16). However, a modification in the control scheme of Fig. 9 is necessary. This consists in including a third input signal from the zero sequence power in the control block where is generated. The proposed control strategy may be suitable in a stiff feeder, where voltage could be considered undistorted

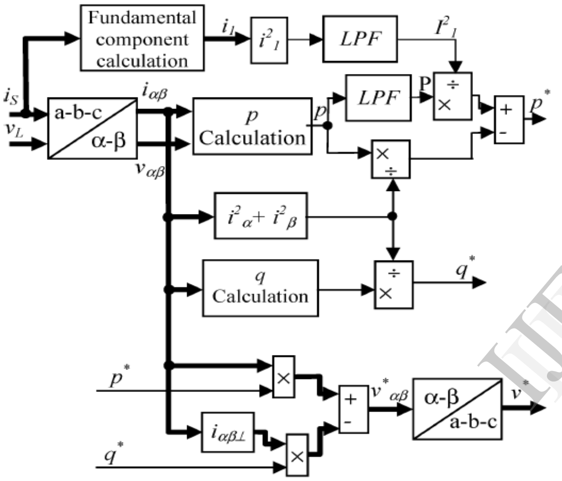


Fig. 6. Control scheme.

IV. SIMULATION RESULTS

The system shown in Fig. 6 has been simulated in the Matlab- Simulink platform to verify the proposed control. Each power device has been modeled using the SimPowerSystem toolbox library. The power circuit is a three-phase system supplied by a sinusoidal balanced three-phase 100-V source with a source inductance of 5.8 mH and a source resistance of 3.6 Ω.

A. Case 1: Nonlinear Balanced Load

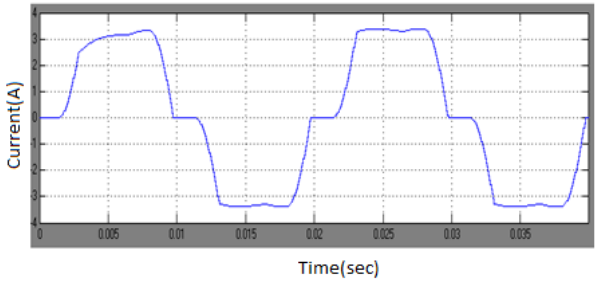
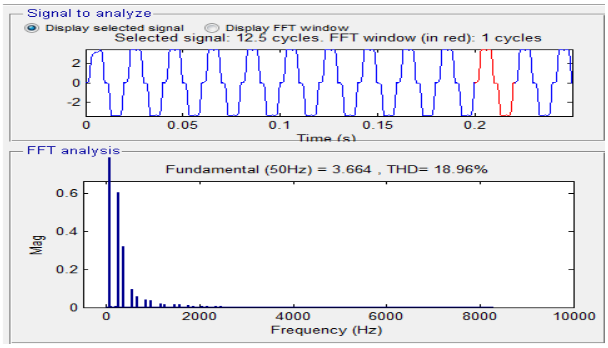


Fig. 7. Load current of the phase "a".



In this case, the nonlinear load consists of an uncontrolled three-phase rectifier with an inductance of 55 mH and a 25 resistor connected in series on the dc side. Fig. 7 shows the phase "a" load current. The load current total harmonics distortion (THD) is 18.6% and the power factor 0.947, when the system is not compensated. The 5th and 7th harmonics are the most important in the current waveform. They are 16.3% and 8.4% of the fundamental harmonic, respectively.

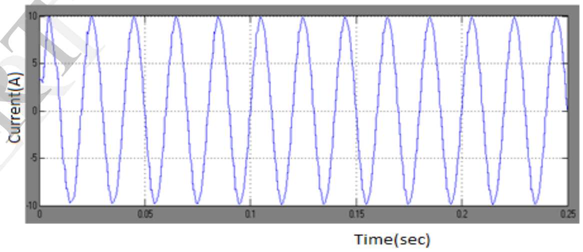
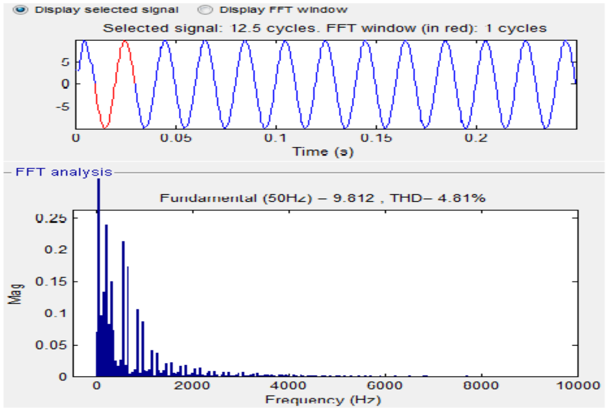


Fig. 8. Source current when the passive filter is connected.



Two LC branches were connected to mitigate the fifth and seventh harmonics. The source current waveform with the passive filter connected is shown in Fig. 8. The THD falls to 4.7%. The 5th and 7th harmonics decrease to 3.6% and 0.9%, respectively. The passive filter was designed only to compensate the source current harmonics; the reactive power was not considered. The power factor of the set load and passive filter is 0.97.

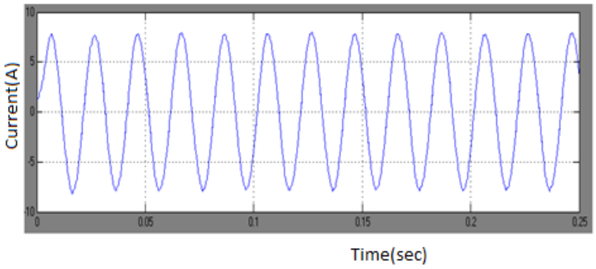
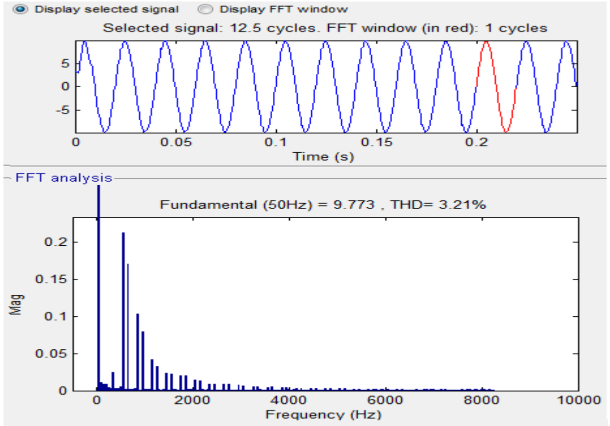


Fig. 9. Source current when the active filter is connected.



Selected signal: 12.5 cycles. FFT window (in red): 1 cycles

Fundamental (50Hz) = 9.773 , THD= 3.21%

When the active filter is connected, the source current THD falls to 3.21%. The waveform is shown in Fig. 11. Now, the power factor rises to 0.99. This allows the proposed control to be verified, the passive filter compensation characteristic to be improved and unity power factor is practically achieved.

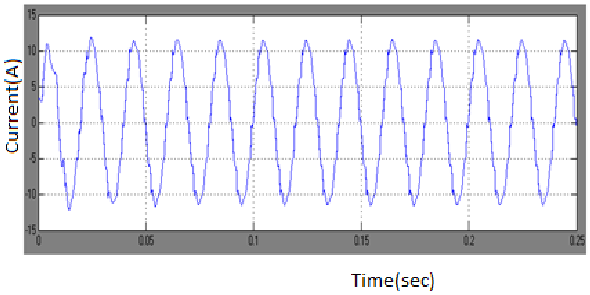


Fig. 10. Source current when passive filter is only connected. Source Impedance, 1.3 Ω and 2.34 mH.

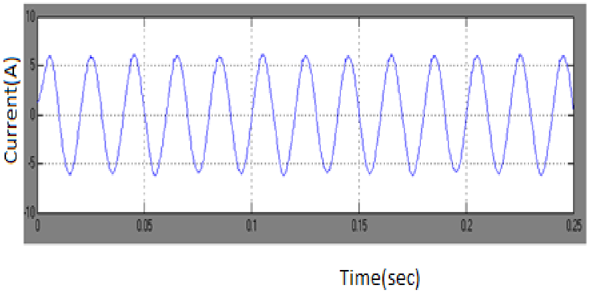


Fig. 11. Source current when the active filter is connected and the resistor on the dc side is 50 Ω.

B. Case 2: Non-Linear Unbalanced Load

In this case, the three-phase load is built with three single phase uncontrolled rectifiers with capacitors and resistors connected in parallel at the dc side with the values shown in Table II. Fig. 16 shows the source currents in the uncompensated system. Current THDs of “a”, “b”, and “c” phase are 18.8%, 35.0%, and 37.6%, respectively.

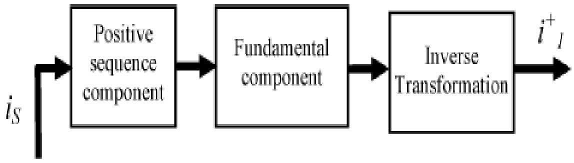


Fig. 12. Modification in the control scheme for unbalanced load.

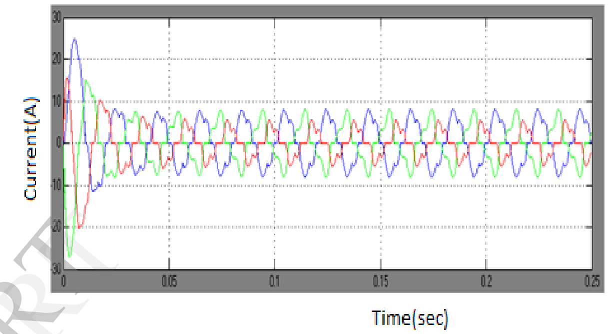
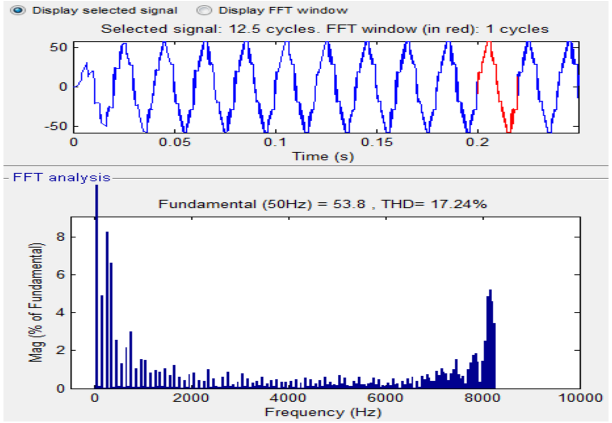


Fig. 13. Source current without filters. Unbalanced load.



Selected signal: 12.5 cycles. FFT window (in red): 1 cycles

Fundamental (50Hz) = 53.8 , THD= 17.24%

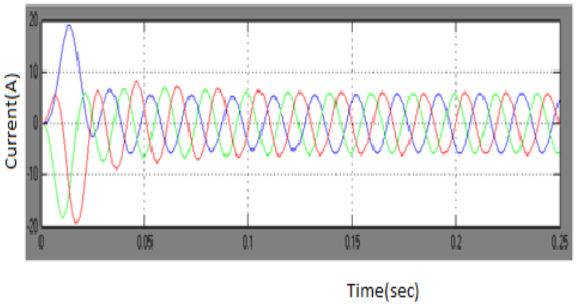


Fig. 14. Source current with active filters and unbalanced load.

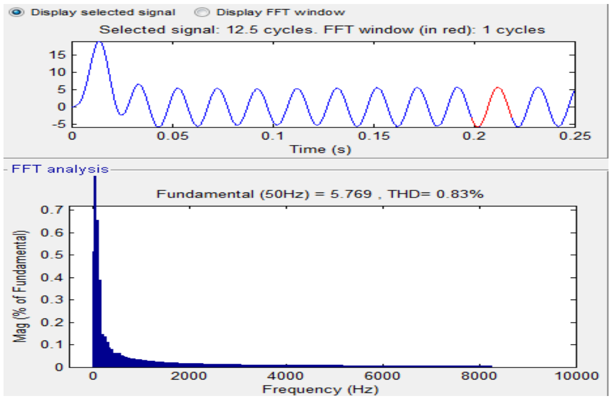


Fig. 18 shows the three source currents when this ontrol is applied to the active filter. The system presents a behavior similar to a resistive and balanced load. The source currents THD are 1.4%, 0.83%, and 1.3% in phases “a”, “b”, and “c”.

VI. CONCLUSIONS

A control algorithm for a hybrid power filter constituted by a series active filter and a passive filter connected in parallel with the load is proposed. The control strategy is based on the dual vectorial theory of electric power. The new control approach achieves the following targets.

—The compensation characteristics of the hybrid compensator do not depend on the system impedance.

—The set hybrid filter and load presents a resistive behavior. This fact eliminates the risk of overload due to the current harmonics of nonlinear loads close to the compensated system.

—This compensator can be applied to loads with random power variation as it is not affected by changes in the tuning frequency of the passive filter. Furthermore, the reactive power variation is compensated by the active filter.

—Series and/or parallel resonances with the rest of the System is avoided because compensation equipment and load presents resistive behavior.

Therefore, with the proposed control algorithm, the active filter improves the harmonic compensation features of the passive filter and the power factor of the load. Simulations with the MATLAB-Simulink platform were performed with different loads and with variation in the source impedance.

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