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Alexandru Bitoleanu, Mihaela Popescu, Vlad Suru

High Performance Shunt Active Power Filter: Design Consideration and Experimental Evaluation

The paper presents an active power filter with high performance, achieved by the authors. To obtain these performances some contributions were brought, both in the power part and in the control part, those are highlighted. First, some design considerations of interface filter are done. Next, the experimental setup is presented and a lot of experimental determinations for different conditions of voltage and load are shown. These and some indices calculated show that, indeed, the achieved filtering platform has very good performances.

Keywords: power filters, reactive power control, harmonic distortion

1. Introduction

In the last years, shunt active power filters (SAPF) based on pulse-width modulated (PWM) voltage-source inverters have been widely studied and developed as a solution to avoid the grid problems generated by distorted currents drawn by the increasing number of nonlinear loads. They improve the power quality by injecting a proper compensation current into the point of common coupling (PCC) so that the supply current system is balanced, harmonic-free and in-phase with the supply voltage system.

Clearly, the efficiency and performance of an SAPF depends essentially on the method implemented to generate the reference currents and the design and implementation of control algorithm. On the other hand, the interface passive filter correctly designed can improve significance of the SAPF.

There are various strategies for generating reference current values, based on either frequency or time domain. Generally, the implemented method must have two main properties: to be applied in really conditions of voltage distortion and to need a low computing time. Among the time-domain-based methods, most approaches, which lead to high filtering performance, implement the p-q theory concepts introduced by professor Akagi and his coauthors in 1983 and subsequently developed by them and other researchers [1]-[4]. This approach allows the global compensation of the load current and the high level of accuracy in current tracking and fast dynamic response [5]-[7].

Usually, two control loops are implemented in SAPF-based compensation systems, with the DC-voltage loop outside the inner current loop [8], [9]. In order to guarantee the active power filter controllability by power losses compensation, the voltage loop must keep the DC voltage in its reference level. For high filtering performances is better that the DC voltage reference to be not constant. The authors developed an original method for an optimal prescribed DC-voltage which minimizes the total harmonic distortion factor of the supply current after compensation.

In this paper, a three-phase three-wire SAPF system and its filtering performances are presented. Section 2 describes the main components of the active filtering system. Next, our contribution in order to design a high performance LCL interface filter is outlined. In section 4, our improving of p-q theory in order to proper operation under nonsinusoidal voltage conditions, is presented. The next section presents the optimal design of voltage PI controllers. Next, the control implementation on the dSPACE 1103 DSP system is presented. Then, in section 7, the experimental results for both balanced and unbalanced loads are illustrated. Finally, some concluding remarks are drawn.

2. Structure of the Shunt Active Filtering System

The adopted structure was a the three-phase three-wire active filtering system composed of a two-level VSI which is connected to PCC through a LCL coupling filter to prevent the high order switching harmonics from propagating into the power supply, distorted current source loads and an industrial PC [10], [11].

The VSI inverter based on SKM100GB123D IGBTs power modules (IC=100 A, VCES=1200 V), having a DC-capacitor of 1100 μF, acts as SAPF to generate the compensating currents. The line-to-line supply voltage is 380 V rms and the apparent power of VSI is 15 kVA.

Two types of distorted balanced/unbalanced loads were used, i.e. an a.c. voltage controller which supplies a three phase inductance (the resistance is very low) and a full controlled three phase bridge rectifier. The first load is the dedicated inductive distorted current source and it has some important facilities:

- The current can be high distorted (THD over 100%);
- The control angles of the each phase group of thyristors can be modified independently, so that the load can become unbalanced;
- It allows dynamic modification of the load current, by sinusoidal modulation of the control angle with settable frequency.

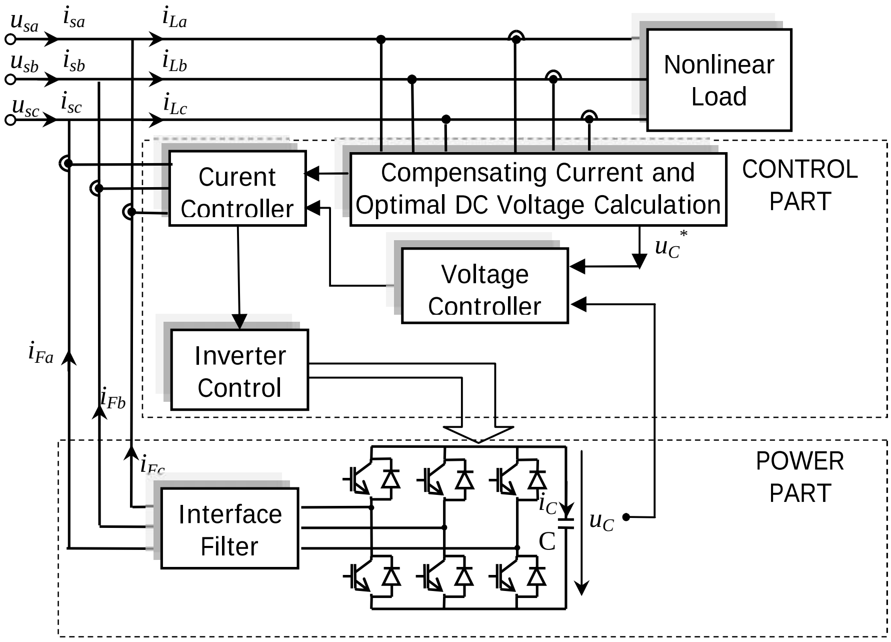


Figure 1. The Structure of a Shunt Active Power Filter.

In the some time, it has the disadvantage that the current is almost purely reactive and, when total filtering is achieved, the remained current network is very small.

The acquisition system based on LEM sensors measures two line-to-line supply voltages, two load line currents, six inverter line currents (three currents in front of the coupling filter and three currents after) and the DC-link voltage.

The industrial PC is equipped with a dSPACE 1103 DSP board which is used for the control and monitoring of entire SAPF system.

Many theories were developed for distortion regime analyzing. They allow the decomposition of the distorted current generated by a nonlinear load and highlighting the useless component [12] - [16]. That is why the main practical application of these power theories is the shunt active power filtering. It must be noted that, starting from the control by current of the inverter, we focused on the current compensated not on powers. So, starting from a distorted load phasor current ($\underline{i}_L$), the shunt active power filter (SAPF) is able to inject such a compensating phasor current ($\underline{i}_F$) in the point of common coupling (PCC) so that the current drawn from the network has the desired shape and zero passing ($\underline{i}_{des}$),

$$\underline{\mathbf{i}}_F = \underline{\mathbf{i}}_{\mathbf{L}} - \underline{\mathbf{i}}_{\mathbf{des}} \,. \tag{1}$$

From the point of view of practical applicability, active filtering can be of two types: partial filtering and total filtering. In the partial filtering case, the supply phase currents are balanced and sinusoidal or they have the same shapes as the voltages. In the total filtering case, the supply currents are balanced and sinusoidal or have the same shapes and zero crossing as the voltages.

On the other hand, if the current is sinusoidal, the goal of filtering is “zero distortion factor” and if the current has the same shapes and zero crossing as the voltage, the goal of filtering is “unity power factor”. So, the desired current can be the sum of the active and reactive components in the partial filtering case and the active component in the total filtering case [17].

Starting from the main theories (Fryze-Buchholz-Depenbrock Theory, Generalized Instantaneous Reactive Power Theory, Generalized Instantaneous Non-Active Power Theory, F. Currents’ Physical Components Theory – CPC, Conservative Power Theory, p-q Theory), the authors developed several computing algorithms for desired current calculus that have been used to control in active filtering.

3. LCL Filter Design

Filter interface of an active power filter is a passive filter used to connect the inverter to the grid voltage (Fig. 2). It is sized to meet these two criteria [18]:

- Provide the dynamics needed to compensate all imposed current harmonics;
- To prevent harmonic components caused by the switching frequency to propagate into the electrical networks.

Second order filter, often called T filter, consists of two inductors (L1 and L2), and a capacity C connected as in Figure 2. It is more efficient compared to first-order filter (L), because it has in addition one degree of freedom provided by capacitance C and can thus ensure both of the sizing criteria [10].

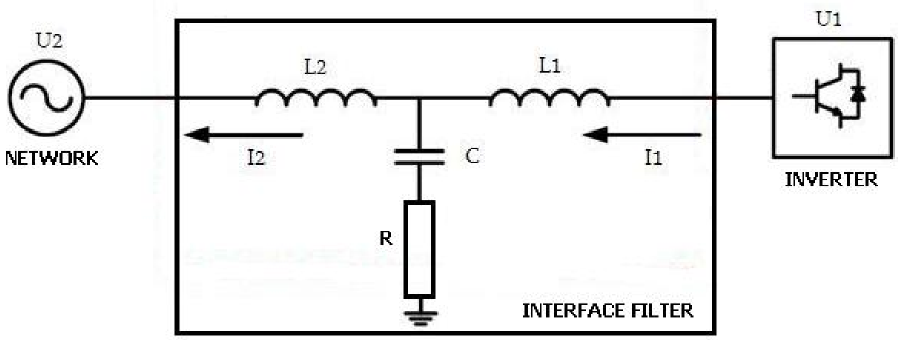


Figure 2. The Structure of second order filter and its conection.

Assuming that, in point of common coupling voltage is sinusoidal, the network will act as a short circuit in relation to the harmonic current and the equivalent circuit is shown in Figure 3.

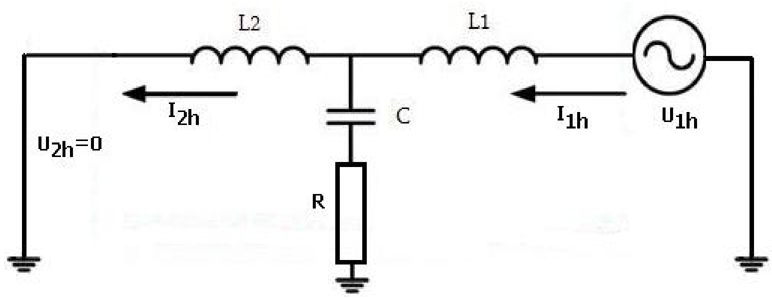


Figure 3. The equivalent diagram on the harmonics 2 to n of the second order filter.

Starting from the equivalent circuit, transfer function corresponding to active filter current in point of common coupling, as output size and output current of the inverter, as input, has the expression,

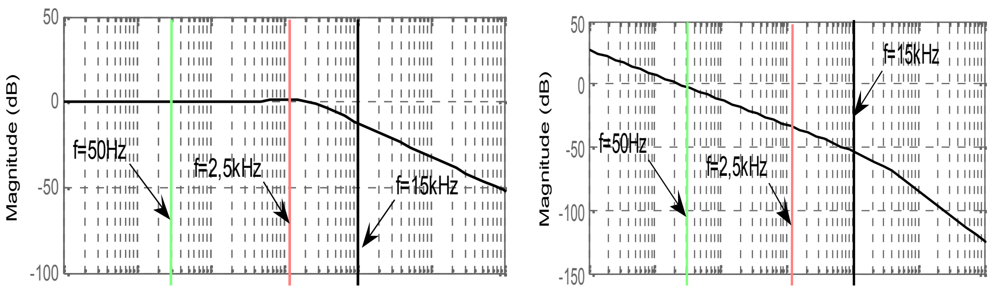
$$\frac{I_2(s)}{I_1(s)} = \frac{1 + RCs}{1 + RCs + s^2 L_2 C}. \tag{2}$$

A first observation is that the transfer function is independent of inductance placed at the output of the inverter. The question is: is it necessary? If we consider the voltage source inverter, the answer is yes. Thus, it follows that the output voltage of the inverter should be considered as input.

$$\frac{I_2(s)}{U_1(s)} = \frac{1 + RCs}{(L_1 + L_2)s + RC(L_1 + L_2)s + L_1 L_2 C s^3}. \tag{3}$$

For properly operation of the filter, the attenuation-pulsation characteristic of the transfer function (2) must satisfy the following conditions (Fig. 4a):

- not to reduce or to amplify the harmonics from 1 to 50;
- start mitigate harmonic currents of order greater than 50;
- at a frequency of 15 kHz corresponding to the average switching frequency, attenuation to be larger.



a) Pulsation [rad/sec] b)

Figure 4. The Bode diagram of the transfer function from relation (2) and (3).

Similarly, the attenuation-pulsation characteristic of the transfer function (3) must satisfy the following conditions (Fig. 4b):

- the fundamental frequency attenuation to be null;
- at a frequency of 15 kHz corresponding to the average switching frequency attenuation to be larger and, if possible, the point to be on maximum negative slope.

4. The Improved p-q Theory

The first version of the p-q theory for active filtering application was published in 1984 in a prestigious international journal by professor Akagi and his coauthors Kanazawa and Nabae [1]. It is also known as the instantaneous reactive power theory for three-phase circuits. The first step was to introduce the instantaneous space vectors ($\underline{u}$ and $\underline{i}$) by transforming the three-phase systems of voltages (u_a, u_b, u_c) and currents (i_a, i_b, i_c) into two-phases orthogonal stationary reference frames (u_α, u_β) and (i_α, i_β). Then, the conventional instantaneous power (p) and the reactive power (q) have been identified as the real and imaginary parts of the instantaneous complex power ($\underline{s}$).

If the non-power invariant transformation a-b-c to d-q is adopted in order to preserve the magnitude of the instantaneous three-phase quantities, the expression of the instantaneous complex power becomes,

$$\underline{\mathbf{s}} = \frac{\mathbf{3}}{\mathbf{2}} \cdot \underline{\mathbf{u}} \cdot \underline{\mathbf{i}}^* = p + jq \,. \tag{4}$$

From here, the current space vector can be expressed as,

$$\underline{\mathbf{i}} = \frac{2}{3} \cdot \frac{\underline{\mathbf{u}}}{|\underline{\mathbf{u}}|^2} \cdot \underline{\mathbf{s}}^* = \frac{2}{3} \cdot \frac{\underline{\mathbf{u}}}{|\underline{\mathbf{u}}|^2} \cdot \left(P + p_\sim - jQ - jq_\sim \right). \tag{5}$$

$$|\underline{\mathbf{u}}|^2 = u_d^2 + u_q^2 \,. \tag{6}$$

In shunt active filtering systems, expression (5) can be used to calculate the reference compensating current or desired line current. From (5), the active and reactive current vectors are,

$$\underline{\mathbf{i}}_{\mathbf{a}} = \frac{2}{3} \cdot \frac{P}{|\underline{\mathbf{u}}|^2} \underline{\mathbf{u}}; \;\; \underline{\mathbf{i}}_r = -j \frac{2}{3} \cdot \frac{Q}{|\underline{\mathbf{u}}|^2} \,. \tag{7}$$

If the total compensation is proposed (the harmonics and the reactive current), the desired line current contains only the active load currents from (7).

But, according to the opinion of the most specialists in the field (Fryze, Shepherd, Zakikhani, Czarnecki, Willems and many others), the active current must have the same shape as the voltage [19, 20, 21]. It means that, in expression (4), the square of voltage space vector magnitude must be constant. However, when the supply voltages are distorted, the magnitude of the voltage space vector is time dependent [22], [23] and the calculation of the desired supply current by (7) leads to a nonsinusoidal waveform of this current which has a different distortion level compared to the voltage distortion (Fig. 5). A mathematical inconsequence of the original p-q theory under non-sinusoidal voltage was pointed out by authors [22], [23], mainly related to the fact that the active current given by (7) has not the same shape as the voltage.

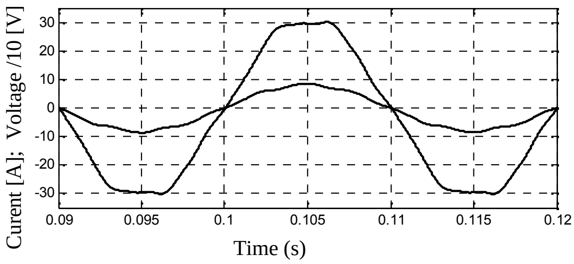


Figure 5. Distorted supply voltage and active load current calculated by (7).

In order to obtain an active current whose waveform has the same shape as the supply voltage, in accordance with Fryze's definition, the denominator in (7) must be constant. The authors demonstrated that the denominator must be the rms value of the voltage vector magnitude,

$$U = \sqrt{\frac{1}{T}\int_{t-T}^{t} \left|\underline{\mathbf{u}}\right|^{2} dt}\ . \tag{8}$$

Thus, the expressions of the true active and reactive currents become,

$$\underline{\mathbf{i}}_{\mathbf{a}} = \frac{2}{3}\cdot\frac{P}{U^2}\underline{\mathbf{u}};\ \underline{\mathbf{i}}_{r} = -j\frac{2}{3}\cdot\frac{Q}{U^2}\ . \tag{9}$$

5. Optimal Controllers Design

For the control of the system, two cascaded control loops were adopted. The control structure includes the optimal DC-link voltage loop outside the inner current loop. A PI controller is adopted to control the voltage across the capacitor. The PI controller parameters have been tuned according to the Modulus Optimum (MO) criterion for an efficient disturbance rejection [24]. In addition, the passband frequency (fp) of the unity feedback system must be imposed.

If the transfer function of the voltage controller is written as

$$G_{Ru}(s) = \frac{1+\bar{}_{1u}\cdot s}{\bar{}_{u}\cdot s} \tag{10}$$

the following expressions can be used to calculate the two time constants [11].

Finally, the PI controller parameters are obtained as a function of the passband frequency:

$$-_{1u} = \frac{0.36}{f_p}; \tag{11}$$

$$-_{u} \approx 0.6495 \cdot \frac{3 \cdot K_{Tu} \cdot U_s}{K_{Ti} \cdot C \cdot U_{DC}} \cdot \frac{1}{f_p^2}. \tag{12}$$

In the expressions (11) and (12), the significance of parameters are: K_{Tu} and K_{Ti} - the proportional constants associated to the voltage and current transducers; U_s - the rms value of the phase voltage; C – DC circuit capacitor and U_{DC} is average voltage of the DC circuit capacitor. The implementation of a specific control system for an optimal prescribed DC-voltage is originated by extensive analysis and experimental results on the active filtering system, when the coupling interface and DC-storage circuit are well defined. It has be pointed out that, for each value of the apparent power to be compensated, there is an optimal value of DC-voltage which minimizes the total harmonic distortion factor of the supply current after compensation [24].

6. Control Implementation on dSPACE 1103 System

To perform the real-time control of the active filtering system, the control algorithm previously described has been built under Matlab/Simulink environment combined with the RTI and RTW tools provided by dSPACE 1103 system (Fig. 6). After normalizing, the digital inputs supplied by ADC blocks are used according to the adopted control strategy (hysteresis controller for current loop and PI controller for DC voltage loop). The generated switching signals are taken out of the DS1103 with the help of six digital outputs through the DS1103BIT_OUT block of Master PPC library. A specific block has been created to control the start-up process of the shunt active power filter and the associated DC-capacitor charging.

In addition, some protections were taken into consideration and validation conditions were used to avoid unexpected behaviours during the system operation.

7. Experimental Results

Using the experimental platform described in sections 2 a lot of methods for compensating current calculation have been implemented. Next, some results obtained by improved p-q method will be presented in order to outline the high performances of developed shunt active power filter system.

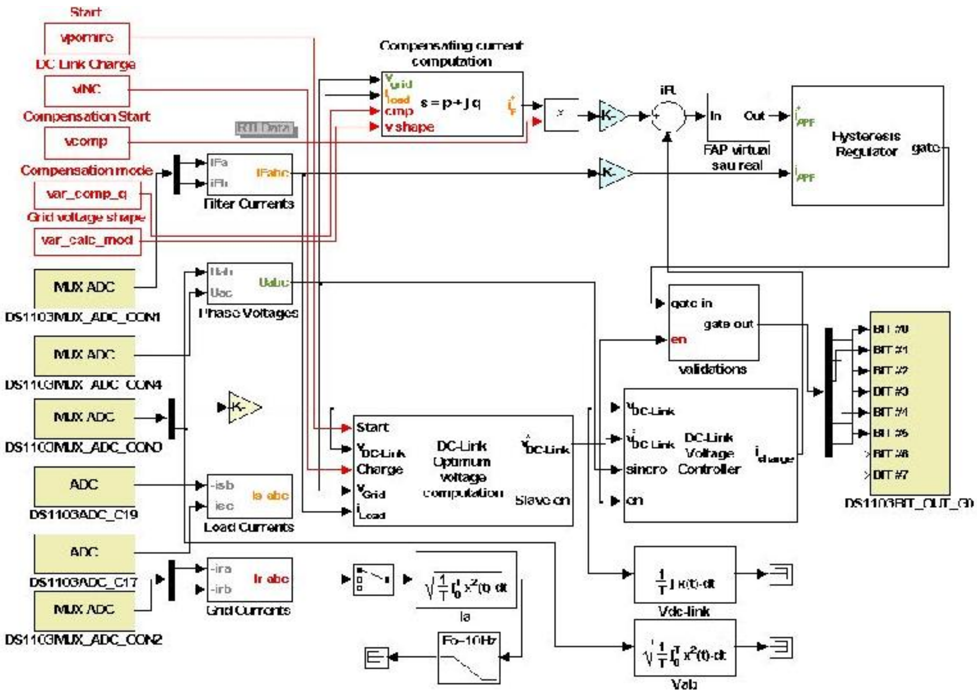


Figure 6. Compiled Simulink model of the control system.

7.1. Case 1: nonlinear and unbalanced load

The first nonlinear load taken into consideration to be compensated is a three-phase controlled thyristor-bridge rectifier with resistive–inductive load on the DC side. When a resistor is connected in series in one line of the transformer secondary, the system of currents drawn from the power supply is unbalanced, as shown in Fig. 7 The rms line currents are 12.5 A, 16.5 A, and 14.6 A, respectively.

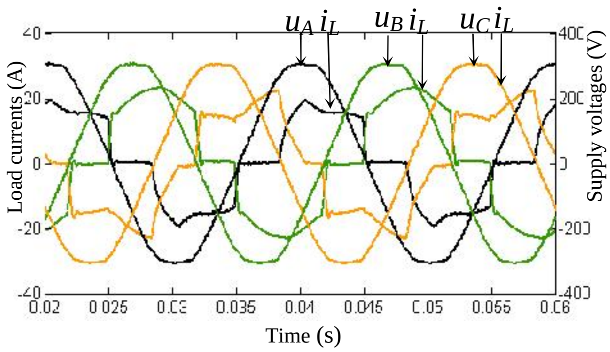


Figure 7. Supply voltages and load currents drawn by the unbalanced rectifier.

The unbalance factor on the fundamental current is 7.22 %.

There are different harmonic spectra of the line currents and the associated harmonic factors are from 20.8 % in line-B to 27.4 in line-A.

By forcing the SAPF to track the calculated reference current for partial compensation, a nearly balanced and sinusoidal system of supply currents is obtained, with a low average harmonic distortion factor of 2.27 % (Fig. 8).

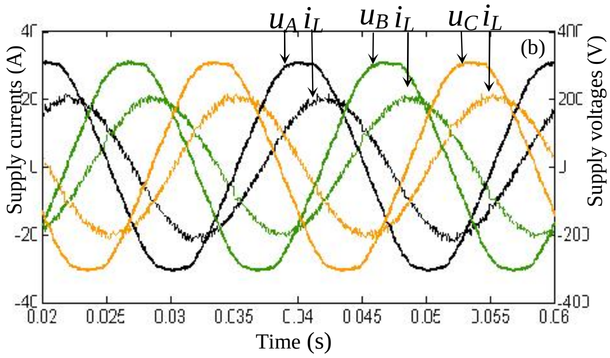


Figure 8. Supply voltages and line currents after partial compensation.

The three-phase rms value of the line currents absorbed from the power supply is almost equal to the load current, but the power factor is increased with about 6%. The active power at the supply side exceeds the load active power by about 4 % to cover the losses in the active filter circuit.

The second load is a AC voltage controller that supplies an unbalanced three-phase inductive load. The voltage is sinusoidal, but the currents are high distorted (over 100%) and unbalanced (Fig. 9). After partial compensation, the line currents are balanced and sinusoidal (Fig. 10). The current is not in phase with the corresponding voltage because its reactive component is not compensated.

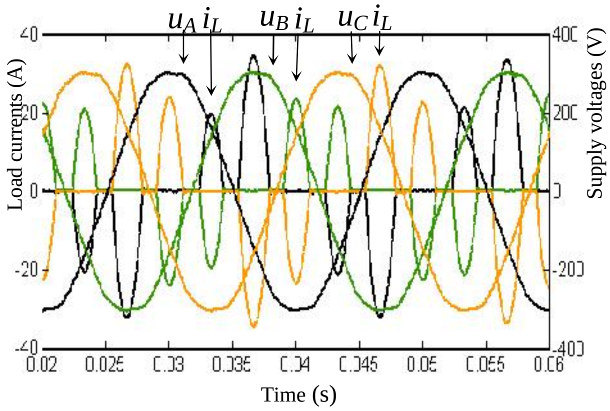


Figure 9. Supply voltages and load currents drawn by the AC voltage controller (unbalanced).

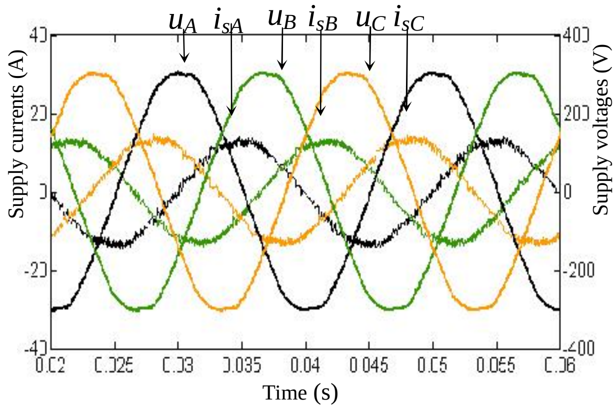


Figure 10. Supply voltages and line currents after partial compensation of AC voltage controller.

7.2. Case 2: nonlinear balanced load and no ideal voltage

In this case, the both types of load have been used under low distorted voltage conditions (about 5%). For the AC voltage controller that supplies a balanced three-phased inductive load, the goal has been harmonics compensation. Opposite, for the three-phase controlled rectifier balanced load, the full compensation has been imposed. In the both cases, very good performances of the active filter system are achieved (the harmonic distortion factor of the line current after compensation is about 3%). Some particularities will be highlighted:

- Figure 11 corresponds to partial compensation of AC voltage controller load and figure 12 corresponds to three phase bridge rectifier load;

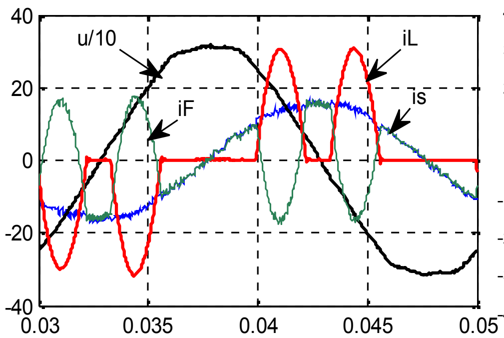


Figure 11. Supply voltage - black, load current – red, active filter current - green and line current after partial compensation– bleu, on one phase (AC voltage controller load).

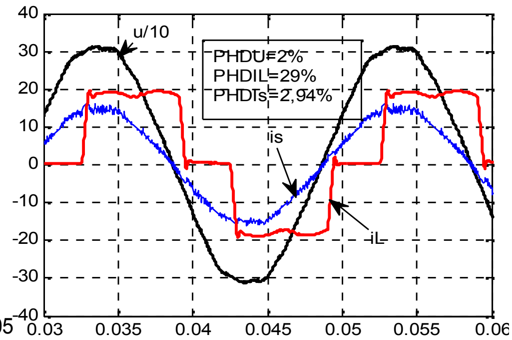


Figure 12. Supply voltage - black, load current – red, active filter current - green and line current after total compensation – bleu, on one phase (Three phase bridge rectifier load).

- It is clear that the phase current and the phase voltage have the same waveform; Moreover, in the total compensation case (Fig. 12), the zero crossings of the supply current and voltage are identical.

8. Conclusion

The goal of the paper is the presentation of high performances active power filter developed by authors in their laboratory. The main contributions to the achievement SAPF refer to:

- Designing a performant interface filter;
- Optimal design of voltage controller and the identification of a method for optimal prescribing of voltage capacitor, according to the power that must be compensated;
- Improving p-q theory, so that it can be applied to non-sinusoidal voltage conditions;
- Implementation of the entire control algorithm on dSPACE1103 system.

The experimental results demonstrate very good performances of the laboratory platform. The obtained values of the filtering efficiency are 23.26 for the three-phase AC voltage regulator (balanced and unbalanced load) and 9.8 for the three-phase controlled rectifier with balanced R-L load.

Even if the line voltage is slightly distorted, the experimental waveforms show the differences between the line current obtained by Akagi and by proposed method. Thus, for total compensation (harmonics and reactive power) through the proposed method, the waveforms of the line current after compensation and the supply voltage are the same and the phase shift between them is zero. This means that the compensated line current is only the active current.

On the contrary, the line current obtained through the compensating current computed in accordance with the Akagi's method has not the same waveform as the supply voltage and it does not represent the active current.

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Addresses:

- Prof. Dr. Eng. Alexandru Bitoleanu, University of Craiova, Electrical Engineering Faculty, Decebal bd. 105, 200440, Craiova, alex.bitoleanu@em.ucv.ro
- Prof. Dr. Eng. Mihaela Popescu, University of Craiova, Electrical Engineering Faculty, Decebal bd. 105, 200440, Craiova, mpopecu@em.ucv.ro
- Lect. Dr. Eng. Vlad Suru, University of Craiova, Electrical Engineering Faculty, Decebal bd. 105, 200440, Craiova, vsuru@em.ucv.ro