LCL Interface Filter Design for Shunt Active Power Filters

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***Abstract*—This paper is focused on finding the parameters of a second order interface filter connected between the power system and the shunt active filter based on switching frequency of the active filter. Many publications on power active filters include various design methods for the interface inductive filter which take into account the injected current and its dynamic. Compared to these ones, the approach presented in this paper is oriented toward the design of the interface filter starting from filter transfer functions by imposing the performances of the filter.**

***Index Terms*— Active filters, Design methodology, Filtering, Passive filters, System analysis and design**

I. INTRODUCTION

Active power filters based on voltage source inverter topology are widely used to improve power quality of nonlinear loads at the point of common coupling to the network.

The switching devices of the voltage source converter bridge are driven with specific control strategies to inject a three phase current into the power supply in order to compensate the load harmonic current, the reactive power and load current imbalance. A DC-bus capacitor is used to provide back-up power (Fig. 1).

To accurately produce the compensating current, the control of power converter is carrier out using pulse width modulation (PWM) methods of high modulation frequency. Since the PWM converter generate undesirable current harmonics around the modulation frequency and its multiples, it is necessary to adopt certain measures to reduce the harmonic distortion of the output current.

Traditionally, a passive filter of L, LC or LCL type is used to interface the voltage source inverter to the power supply.

Usually, the interface filter is designed to satisfy the following two criteria [1]:

- to ensure the dynamic behavior of the current, i.e.

$$\frac{d}{dt} I_{Lh} = \frac{d}{dt} I_c \,, \tag{1}$$

where I_{Lh} is the harmonic current of the load and I_c is the current injected by the active filter;

- to prevent the harmonic components generated by the switching frequency from propagating into the power network.

Two types of interface filters are commonly used, a first order filter and a second order filter.

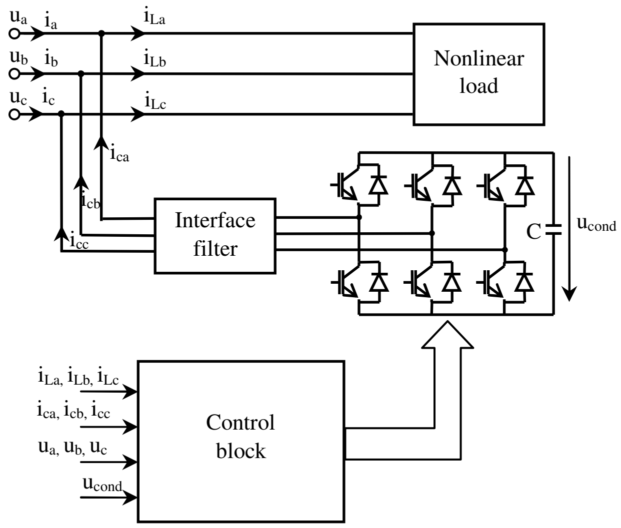


Fig. 1 Basic structure of a three phase active power filter

A. *First order filter*

The first order passive filter called injection inductor is the most used solution to connect the active power filter to the point of common connection. It consists of an inductor having the inductance L_f and the internal resistance R_f.

Such a filter does not allow to satisfy simultaneously the two design criteria.

In essence, the only viable value of the inductance complies with (1) and leads to a good dynamic of the active filter.

In the worth case scenario, a low value of L_f allows most of switching harmonic currents to flow into the power network and consequently to disturb adjacent electrical equipments. In practice, the first order L type filter cannot usually provide sufficient attenuation for the modulation frequency current harmonics.

On the contrary, a high value of the injection inductor prevents the harmonic currents from propagating into the supply system but affects the active filter dynamic and the quality of compensation diminishes.

Therefore, a good design of the first order passive filter is a compromise between the dynamic and the effectiveness of the active power filter.

B. Second order filter

This type of filter comprises two inductors and a capacitor connected in a T-section as it is shown in Fig. 2.

The popularity of the LCL filter among all output filters used in the field of power electronic applications is due of the fact that a good attenuation is achieved with a reasonable filter cost.

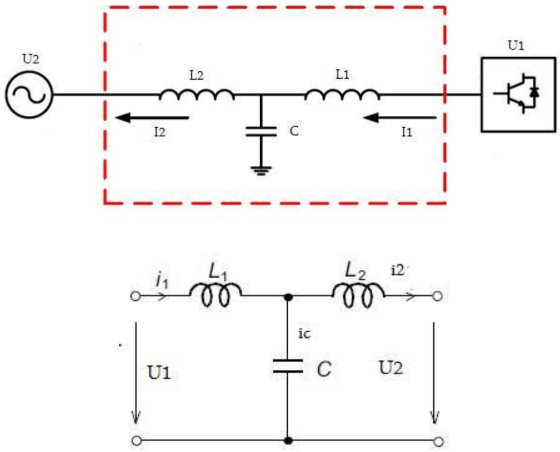


Fig. 1 Equivalent schema of the LCL interface filter

II. TRANSFER FUNCTION OF THE SECOND ORDER FILTER

The equivalent configuration of the filter in Fig.3 shows that, if the supply voltage is sinusoidal, the filter behaves like a short-circuit related to superior order harmonics.

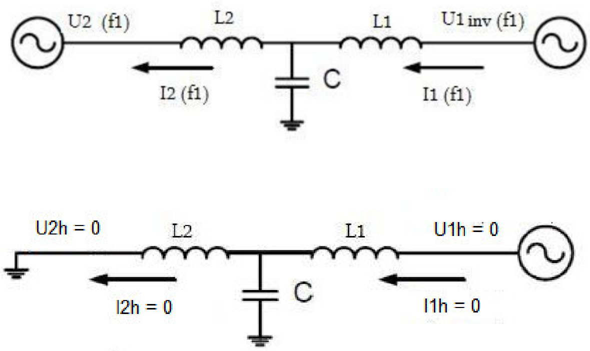


Fig. 3 Equivalent configurations of the interface filter at the fundamental and harmonic frequencies

According to Kirchhoff's laws, the following equations can be expressed:

$$i_1 = i_2 + i_c, \tag{2}$$

$$u_1 - u_c = L_1 \frac{di_1}{dt}, \tag{3}$$

$$u_c - u_2 = L_2 \frac{di_2}{dt}, \tag{4}$$

$$i_c = C \frac{du_c}{dt}. \tag{5}$$

In the domain of the Laplace transform, the above equations become:

$$I_1(s) = I_2(s) + I_c(s), \tag{6}$$

$$\frac{I_1(s)}{U_1(s) - U_c(s)} = \frac{1}{sL_1}, \tag{7}$$

$$\frac{I_2(s)}{U_c(s) - U_2(s)} = \frac{1}{sL_2}, \tag{8}$$

After some processing steps, the expressions (6)-(8) take the following form:

$$I_1(s)\left(1 + s^2 L_1 C\right) = I_2(s) + sCU_1(s), \tag{9}$$

$$I_2(s)\left(1 + s^2 L_2 C\right) = I_1(s) - sCU_2(s), \tag{10}$$

$$U_c(s) = I_c(s)\frac{1}{sC}. \tag{11}$$

Fig. 4 illustrates the block diagram associated to the (6), (7) and (8) expressions.

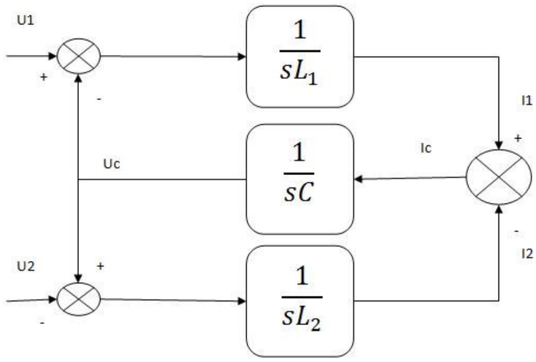


Fig. 4 Block diagram of the second order interface filter

Thus, applying the transfiguration theorem gives the following equivalent transfer functions [5]:

$$\frac{I_1(s)}{U_1(s)} = sC\frac{1 + s^2 L_2 C - \frac{U_2(s)}{U_1(s)}}{\left(1 + s^2 L_1 C\right)\left(1 + s^2 L_2 C\right) - 1}, \tag{12}$$

$$\frac{I_2(s)}{U_1(s)} = sC\frac{1 - \frac{U_2(s)}{U_1(s)}\left(1 + s^2 L_1 C\right)}{\left(1 + s^2 L_1 C\right)\left(1 + s^2 L_2 C\right) - 1}, \tag{13}$$

Supposing that the input and output quantities are harmonic currents i_1 and i_2, condition $U_2(s)=0$ allows expressing the equivalent transfer function:

$$\frac{I_2(s)}{I_1(s)} = \frac{\dfrac{sC}{\left(1 + s^2 L_1 C\right)\left(1 + s^2 L_2 C\right) - 1}}{sC\dfrac{1 + s^2 L_2 C}{\left(1 + s^2 L_1 C\right)\left(1 + s^2 L_2 C\right) - 1}}, \tag{14}$$

Thus, it can be arranged as:

$$\frac{I_2(s)}{I_1(s)} = \frac{1}{1 + s^2 L_2 C}. \tag{15}$$

III. FILTER PARAMETERS

In order to find the frequency characteristics of the filter, the transfer function is arranged in the standard form of a second order system which makes evident the resonance natural frequency ω_n and the damping ratio ξ [5],

$$H(s) = \frac{1}{T^2 s^2 + 2\xi T s + 1} = \frac{\omega_n^2}{s^2 + 2\xi\omega_n s + \omega_n^2}. \quad (16)$$

Taking into account (15), it results:

$$2\xi T = 0, \quad (17)$$

i.e.

$$\xi = 0, \quad (18)$$

$$T = \sqrt{L_2 C}, \quad (19)$$

$$\omega_n = \frac{1}{\sqrt{L_2 C}}. \quad (20)$$

The attenuation versus frequency characteristic in Fig. 5 illustrates the maximum attenuation at natural frequency and a attenuation of -40dB/decade over the cutoff frequency.

$$\omega_{cutoff} = \sqrt{2}\omega_n. \quad (21)$$

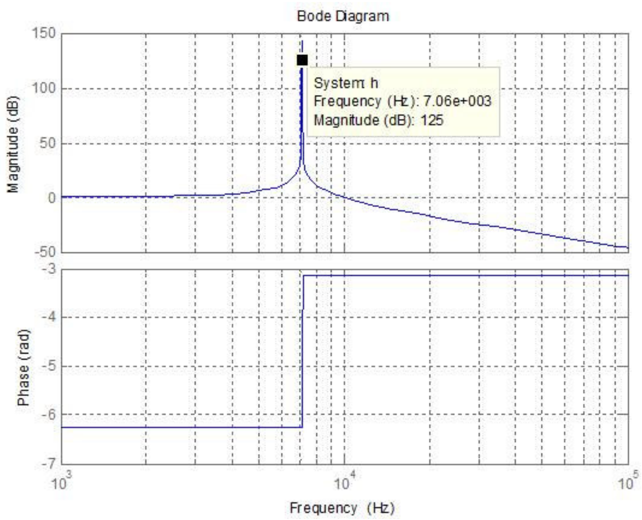


Fig. 5 Frequency response of interface filter

From the operation point of view, the interface filter has to reject the switching harmonics without affecting the harmonics to be compensated. For this reason, the cutoff frequency must be below the switching frequency in order to obtain a rejection current slope of -40dB/decade.

Besides, the minimum frequency which determinates the filter pass band must exceed the highest harmonic frequency to be compensated by the active power filter.

Hence, taking into account condition (5) and the superior pass band limit of $f_n/\sqrt{2}$ which has no influence on the input signal, the following conditions are expressed:

$$f_s \geq \sqrt{2} f_n = \frac{1}{\sqrt{2}\pi \cdot \sqrt{L_2 C}}, \quad (22)$$

$$f_N \leq \frac{1}{2\sqrt{2}\pi \cdot \sqrt{L_2 C}}, \quad (23)$$

where f_s is the switching frequency and f_N is the lowest frequency among the harmonic frequencies to be rejected by the interface filter.

The previous expressions can be written as:

$$\sqrt{L_2 C} \geq \frac{1}{2\pi^2 f_s^2}, \quad (24)$$

$$\sqrt{L_2 C} \leq \frac{1}{8\pi^2 f_N^2}, \quad (25)$$

respectively

$$\frac{1}{2\pi^2 f_s^2} \leq \sqrt{L_2 C} \leq \frac{1}{8\pi^2 f_N^2}. \quad (26)$$

By imposing f_s = 10 kHz and the highest order of the harmonic to be filtered N=50 (i.e. f_N = 2.5 kHz), the inequalities (26) became

$$0.5066 \cdot 10^{-9} \leq \sqrt{L_2 C} \leq 2.0624 \cdot 10^{-9}. \quad (27)$$

As the product L_2C domain is large, the filter behavior will be analyzed for different values of this product as well as for different values of L_2 and C.

IV. FILTERING PERFORMANCES

Computer simulations have been carried out in order to determine the performances of the interface filter.

The nonlinear load consists of a full three-phase controlled rectifier supplying a DC motor.

The task of the shunt active power filter is to compensate both the superior order harmonics and the reactive power.

A DC-bus voltage of 600V and a rms harmonic current of 10A have been taken into consideration.

The filtering performances have been appreciated by comparing the current injected before and after filtering as well as by comparing the supply current with and without interface filter.

Thus, the effectiveness of the interface filter is illustrated in Fig. 6 which shows the output current of the active filter. It oscillates around the set point at the switching frequency of the voltage inverter and the associated error exceeds 5A (Fig. 6a).

It can be seen that the oscillations are much diminished (about ± 1.5 A) at the output of the interface filter. Moreover, there are a lot of zones where the output current is superposed on its set point (Fig. 6b).

The harmonics spectra in Fig. 7 before and after filtering point out even better the efficiency of the interface filter. As it can be seen in Fig. 7a, the output current of the active filter before interface filter also contains, beside the harmonics to be compensated (bellow 51st order), other superior harmonics up to 250th order among the most significant ones are grouped round the 200th order which corresponds to the switching frequency of 10 kHz. Their weight related to the fundamental component required to compensate the reactive power gets near to 20% (Fig. 7a).

On the other hand, the harmonics up to 50th order of the current after the interface filter are left unchanged while the other harmonics are strongly attenuated (Fig. 7b). For instance, the harmonic family grouped round the switching frequency is attenuated to about 5%.

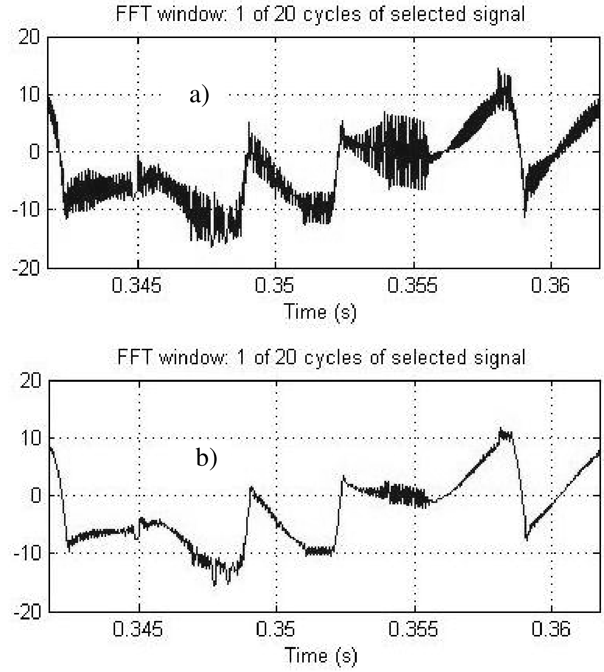


Fig. 6 Current provided by the active filter:
a) before filtering; b) after filtering

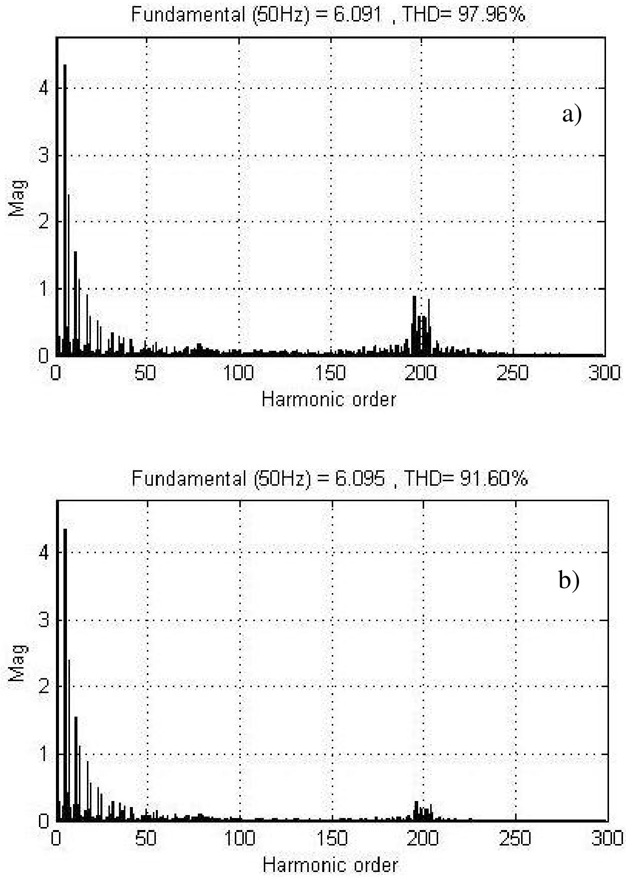


Fig. 7 Harmonics spectra of the current provided by the active power filter: a) before interface filter; b) after interface filter

Very significant is the weight of superior order harmonics which is defined as

$$P_{k=51:300} = \frac{\sqrt{\sum_{k=51}^{300} I_k^2}}{I_1}, \qquad (26)$$

where I_1 is the fundamental component of the useful load current after filtering. This weight value is of.... before filtering and of ... after filtering.

The same aspects are pointed out by the waveform of the supply current with and without interface filter (Fig. 8). Very relevant is the value of the total harmonic distortion factor (THD) which diminishes from 15.39% to the acceptable value of 7.86% after filtering. Moreover, to emphasize the filtering effectiveness, the magnitudes of the harmonics to be compensated provided by the reference current calculation block are compared with those of the harmonics injected into the supply network (Fig. 9).

It can be noticed a little attenuation of the harmonic magnitude starting with the 5th order, but influence of this attenuation on the current THD does not exceed 1%. Besides, it can be seen that the interface filter introduces undesirable harmonics into the power system, such as the 6th harmonic, whose weight is, nonetheless, insignificant.

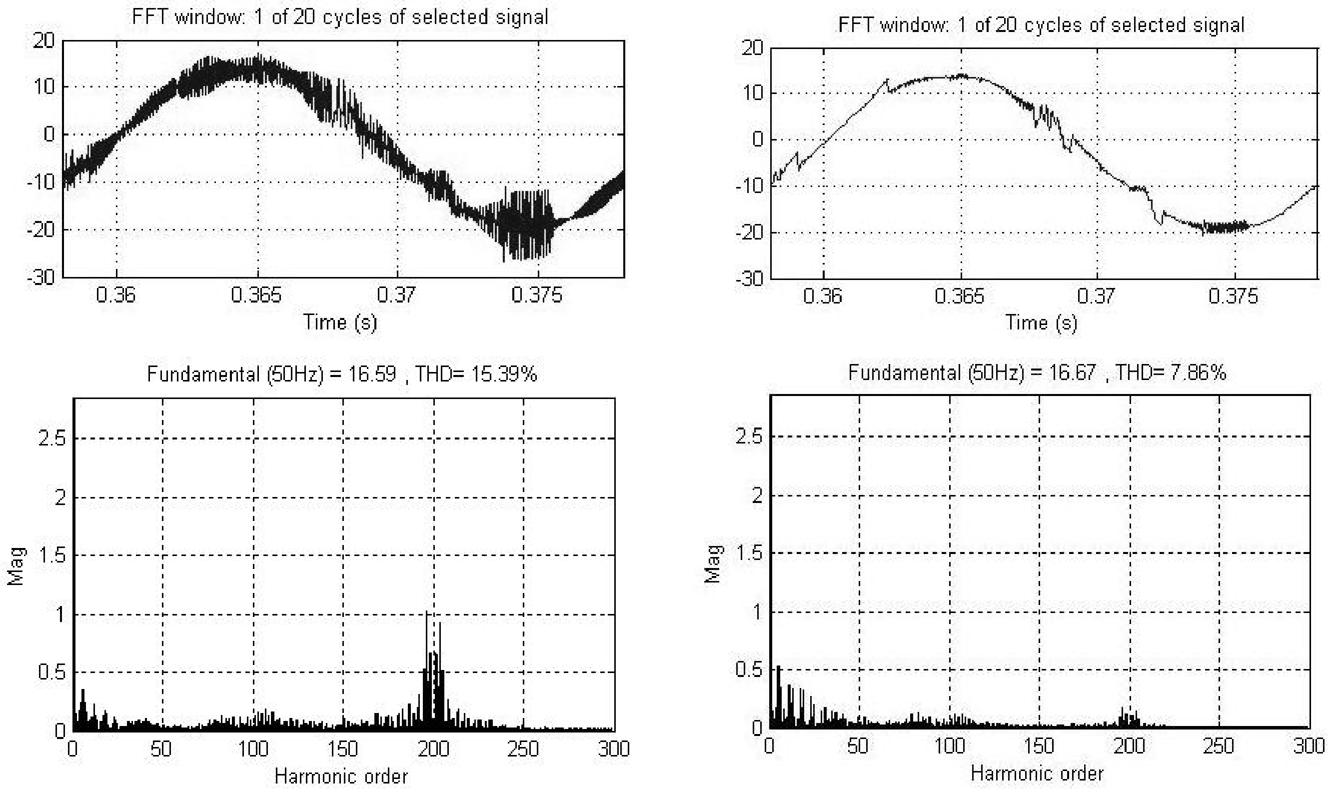
V. OPTIMUM DESIGN OF THE INTERFACE FILTER

As the inequality (26) is not sufficient to determinate the interface filter parameters, the detailed analysis of the influence of the values of product L_2C and of the two parameters (L_2 and C) on the total harmonic distortion factor of the supply current allowed us to point out the following conclusions:

1. There is an optimum value of product L_2C which leads to a minimum value of the current THD (Fig. 10). This one corresponds to the minimum value given by relation (26) .
2. At the optimum value of the L_2C product, the supply current THD can be reduced by increasing the inductance value.
3. The increase of the inductance L_2 over 4mH requires the increase of voltage across the compensation condenser in order to ensure the dynamic behaviour of the current.
4. For the analyzed situation, the minimum value of THD corresponds to $L_2 = 5$ mH; $C = 0{,}1\mu F$.

The correct design of the interface filter parameters has also a positive influence on the dynamic performances of the active power filter.

Thus, as it can be seen in Fig. 11, the filtering process starts immediately after connecting the active power filter to the power line and the line current waveform is close to a sinusoide.



a) b)

Fig. 8 Power supply current waveform and its harmonic spectrum: a) unfiltered ; b) filtered

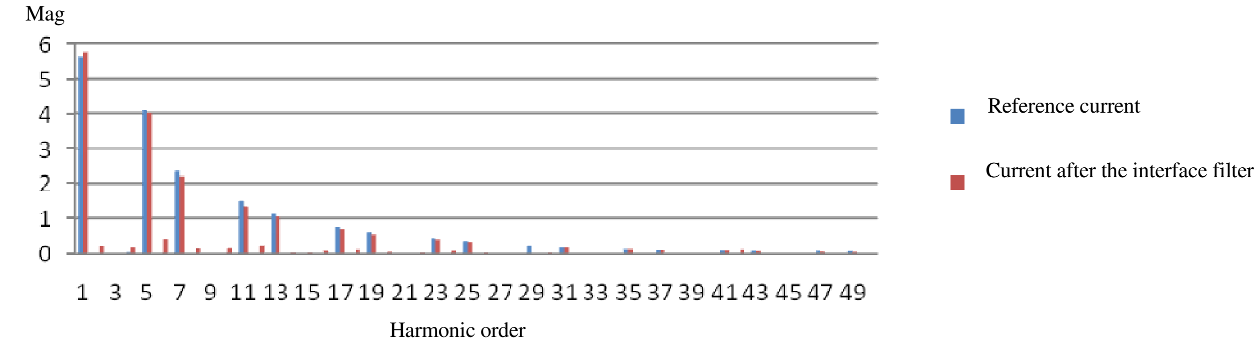


Fig. 9 Comparison between the harmonic spectra of the reference current (to be compensated) and the current after the interface filter

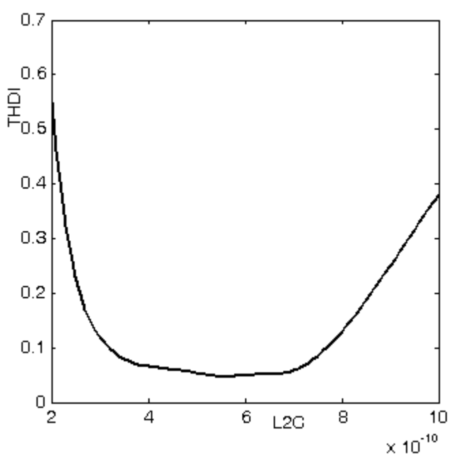


Fig. 10 Total harmonic distortion factor of the supply current versus product L2C for $C = 0{,}1\mu F$

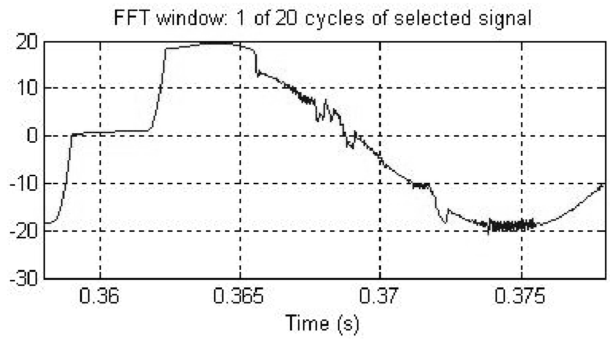


Fig. 11 Dynamic response of the active power filter

VI. CONCLUSION

This paper presents on a new approach of the interface filter design by imposing its performances based on filter transfer functions taking into account the switching frequency of the active filter. The performances refer to the significant attenuation of the switching harmonics without affecting the harmonics to be compensated and they are achieved by imposing the cutoff frequency and the pass band amplification. By a correct choice of the inductance value, the filter behavior is significantly improved and the imposed criteria for such a filter are ensured.

If the switching frequency is chosen to be below the cutoff frequency of the interface filter but over the frequency of the highest-order harmonic to be compensated (e.g. 5kH for a switching frequency of 10kH), the filter operation is much improved by the significant diminution of the switching harmonics of 100th and 200th orders.

It is shown that the minimum supply current THD can be obtained by choosing the minimum value of the product of inductance and capacitance according to relation (26). Moreover, the inductance value which minimizes the supply current THD is about 4mH.

By using an interface filter designed in accordance with the proposed method, the obtained power supply current agrees to the existing standards [6], [7].

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