PERFORMANCE IMPROVEMENT FOR A SINGLE-PHASE SHUNT ACTIVE POWER FILTER

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Active power filters represent a modern solution for improving electrical power transmission efficiency by eliminating the polluting influence of nonlinear loads on the supply grid. This paper analyses and implements a single-phase shunt active power filter with sliding mode control. The proposed control scheme aims to compensate the effect of the non-sinusoidal supply voltage on the filtered line current and to obtain a better dynamic behavior at low total harmonic distortions of the line current. Experimental results are presented, that confirm the previous theoretical analysis.

Keywords: Single-phase active power filter, sliding mode, inverter control, dynamic behavior

1. Introduction

Electrical energy is transmitted through the distribution grid and is used by various consumers in a most efficient manner if the voltage and the current are both sinusoidal and in phase. Alterations of the sinusoidal shape and phase-shifts between voltage and current are introduced by various types of loads and are considered to be polluting factors that have to be kept in certain limits. For the simple case of inductive or capacitive loads, compensating LC filters were implemented in the past, which corrected unwanted phase-shifts. These filters have bulky dimensions and fixed characteristics, which make them applicable only in certain well established situations. Supplementary, the reactive components could cause uncontrolled resonances between various loads connected also to the grid.

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In the last decades more and more electrical loads comprise switching power converters, nowadays implemented at very large scales, which are fundamentally nonlinear loads, due to their time varying topology. These nonlinear loads introduce phase-shifts and also harmonic components in both voltage and currents, thus affecting the quality of power delivered to other users. A modern and effective solution for restoring power quality is represented by power active filters, that are based on switching power converters, controlled in a manner that generates the same distortions as the nonlinear loads, but of opposite sign, thus keeping the supply grid unpolluted. Active power filters are applied to single-phase systems [1]-[3], [7]-[9] or to three-phase systems [4]-[6] and they are connected series or parallel to the nonlinear load, correcting correspondingly mainly the supply voltage or the current drawn from the grid. Shunt active power filters are connected in a point of common coupling (PCC), as shown in Fig. 1.

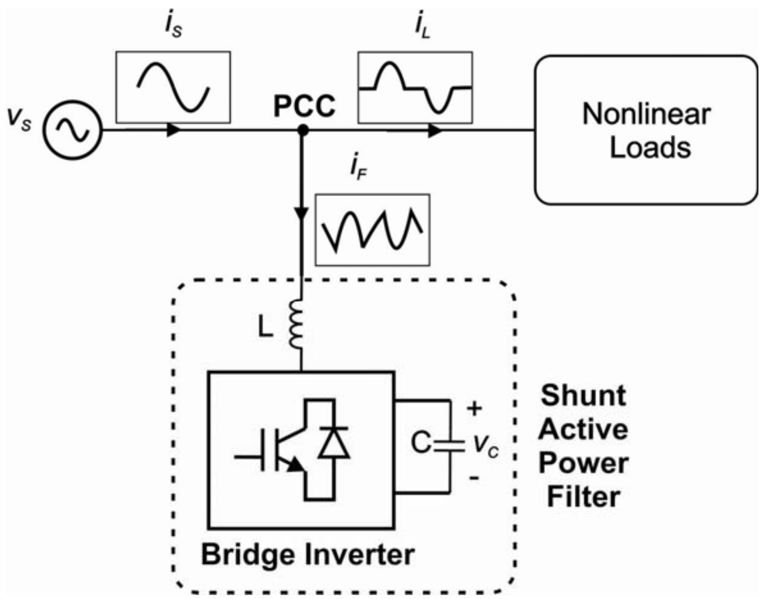

Fig. 1. Parallel connected active power filter

The bridge inverter is driven on the d.c.-side by a capacitor *C* that charges from the grid at a voltage level higher than the maximum voltage at PCC. The controlled currents at the output of the inverter are introduced in the PCC by means of an inductor, *L*. Determined by the nature of the nonlinear loads, the currents that have to be compensated by the shunt active power filter are fast-varying and the response of the filter must be accordingly. Classical PWM control of the inverter bridge inside the active filter does not provide proper performance and thus a more suitable method, well adapted to topology changes, is often applied: sliding mode control. Sliding mode control will force one or more state variables of the system to follow a certain multidimensional path, named sliding surface. The error or deviation from the ideal trajectory will determine the states of the power switches inside the inverter, in order to reduce that error. In order to obtain a as sinusoidal as possible current i_S drawn from the grid, different sliding mode implementations have been proposed so far. For single-phase active power filters, the reference current i_S^* is mostly determined as being proportional to the supply voltage v_S, supposed to be sinusoidal,

$$i_S^* = k \cdot v_S \tag{1}$$

where k is a proportionality factor determined by the power absorbed by the nonlinear load. The straight forward error is defined in [1] as the difference between the actual current and the reference current. By equaling the error to zero, the sliding surface is then obtained. In order to reduce the steady state error in tracking the reference current, in [2] the sliding surface contains also besides the error, the integral of the error. A new error was defined in [3] by multiplying the previous error with the supply voltage and integrating this product. The sliding surface comprises then the error, her derivative and her integral, pondered by sliding coefficients.

Besides the reduced harmonic content of the line current, another goal is to obtain a good dynamic behavior of the shunt active power filter, as the nonlinear load varies, these two desiderates being in contradiction.

This paper proposes a very simple method to obtain sinusoidal shaped line current even in the presence of line voltage distortions and an advantageous tradeoff between reduced THD of the line current and a good dynamic response of the active power filter, presenting also experimental results.

The paper is organized as follows: section 2 explains the functioning of the single-phase shunt active power filter, section 3 analyses the sliding mode control, section 4 presents experimental results regarding steady-state and dynamic operation and section 5 offers the conclusion of this work.

2. Shunt Active Power Filter

Fig. 2 shows the block diagram of the single-phase shunt active power filter. The voltage source inverter bridge is current controlled and connected in parallel to the nonlinear load by means of a coupling inductance L. The large d.c.-side capacitor C charges from the grid at a voltage that is greater than the amplitude of v_S, thus giving the possibility to control the current flow through L_F. The inverter switches are implemented with IGBT transistors with anti-parallel diodes, beeing unipolar in voltage and bipolar in current. The filter current i_F can be increased or decreased by proper control of the inverter switches, depending on the positive or negative half-cycle of v_S. During the positive half-cycle the current i_F becomes more positive, by setting $v_X=0$. If the inverter switches are controlled for setting $v_X=v_C$, then the current i_F decreases towards zero, because always $v_C>|v_S|$. During the negative half-cycle of vS, by setting $v_X=0$ we force the current i_F to become more negative and for $v_X=-v_C$ we will direct the current i_F to increase. These simple goals can be achieved by a unipolar control mode for the inverter bridge, for which the switches S3 and S4 will be controlled depending on the corresponding half-cycle of the supply voltage and will set $v_X\leq 0$ or $v_X\geq 0$, and the switches S1 and S2 will set the increasing or decreasing of the current i_F on each half-cycle correspondingly [1].

This unipolar control mode has the advantage of a reduced number of commutations for the semiconductor switches, but in waveform of the line current i_S, distortions occur during the zero-crossings. In order to eliminate these distortions we will implement, but only during the zero-crossings, the bipolar control mode for the inverter, meaning that S1 and S4 are both switched simultaneously on or off , complementary to S2 and S3. A threshold voltage V_P will determine the width of the window in which the inverter will be controlled in bipolar mode: $-V_P \leq v_S \leq V_P$.

With the notations from Fig.2, the mathematical model of the inverter [1], [3] functioning in the above conditions is:

$$C\frac{dv_C}{dt} = (u_1 + u_4 - 1)i_F \tag{2}$$

$$L\frac{di_F}{dt} = v_S - v_x = v_S - (u_1 + u_4 - 1)v_C \tag{3}$$

where u_1 and u_4 are 1 or 0, depending on the on or off state of the switch S1, respectively S4.

Fig. 2 also shows the control circuit of the inverter, which comprises two control loops. The inner loop controls the current variation and has to be fast and

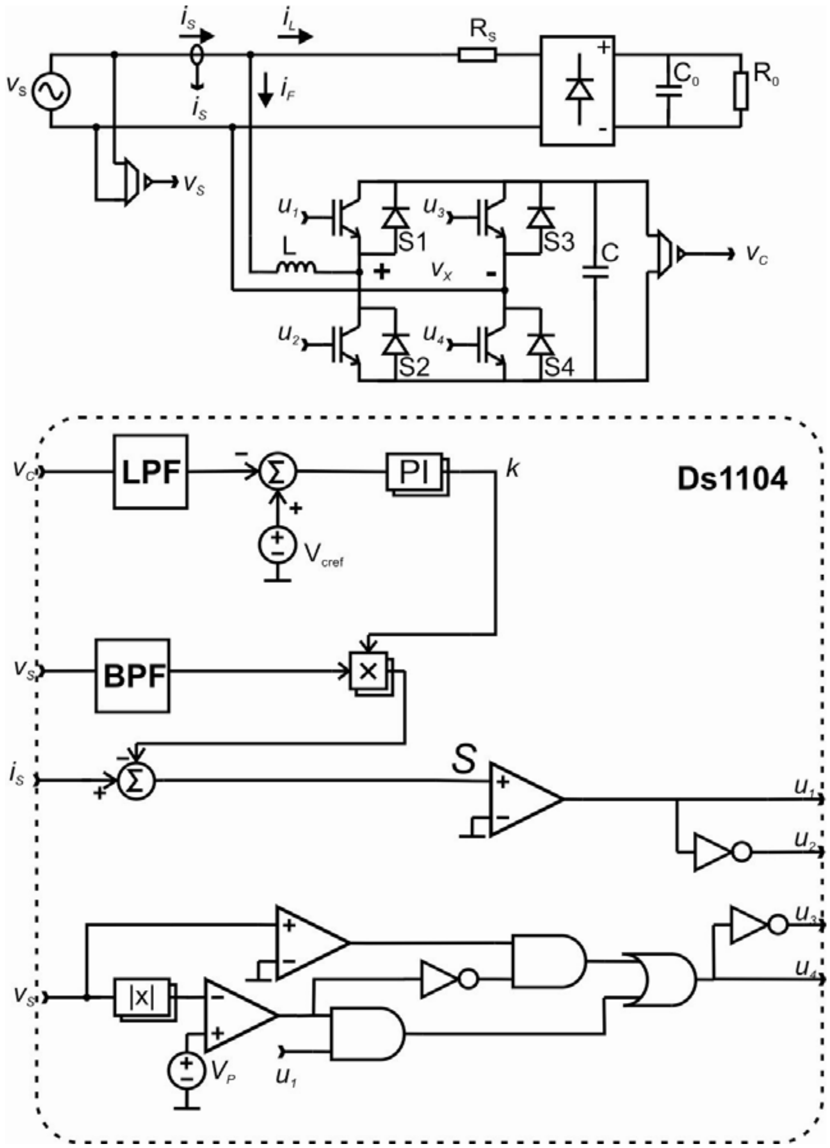

Fig. 2. Implemented Shunt Active Power Filter

the outer loop controls the d.c. voltage of the inverter. The inner loop will track the reference current using sliding mode control, characterized by the possibility of fast changes and the outer loop uses a PI controller that offers the proportionality factor *k* in (1) and has to be tuned out of two contradictory considerations. First, the reference current $i_S^* = k \cdot v_S$ must be as sinusoidal as possible, and assuming an ideal grid voltage, it results that k must vary as less as possible during one cycle of the supply voltage. But also, the variation speed of k will determine the dynamic behavior of the system and a small variation speed of k will result in a poor dynamic response. A good compromise between the two demands is necessary.

3. Sliding Mode Control

The sliding surface equals an ideal trajectory that we wish some chosen state variables to follow. In our case we will control the inverter in such a manner that the line current i_S results of the same shape (ideal sinusoidal) and in phase with the supply voltage v_S. Thus the reference line current is of the form mentioned in (1).

We define the error function:

$$x_1 = i_s - kv_s \tag{4}$$

By equaling (4) to zero we obtain a simple to implement but effective sliding surface.

The existence of sliding mode control under the given conditions is checked by determining whether the equivalent control stays within the boundaries [0,1].

The expression for the equivalent control is derived from the condition $\dot{S} = 0$, or

$$\dot{S} = \dot{x}_1 = 0 \tag{5}$$

Considering that:

$$i_S = i_F + i_L \tag{6}$$

And using (3) and (6), equation (5) becomes:

$$\dot{S} = v_S - (u_1 + u_4 - 1)v_C + L\left(\dot{i}_L - k\dot{v}_S\right) = 0 \tag{7}$$

or,

$$u_1 + u_4 = 1 + \frac{v_S}{v_C} + \frac{L}{v_C}\left(\dot{i}_L - k\dot{v}_S\right) \tag{8}$$

The expressions of the equivalent control for unipolar and bipolar operation mode of the inverter are:

- For $v_S \geq V_P$ and $v_S \leq -V_P$ (unipolar control) , we have

$$u_4 = \frac{1 + sgn(v_S)}{2}$$

and we obtain:

$$u_{1eq} = \frac{1-\mathrm{sgn}(v_S)}{2} + \frac{v_S}{v_C} + \frac{L}{v_C}\left(\dot{i}_L - k\dot{v}_S\right) \tag{9}$$

- For $-V_P \leq v_S \leq V_P$, (bipolar control), we have $u_1 = u_4$

and we obtain:

$$u_{1eq} = \frac{1}{2} + \frac{v_S}{2v_C} + \frac{L}{2v_C}\left(\dot{i}_L - k\dot{v}_S\right) \tag{10}$$

Equations (9) and (10) satisfy the conditions for existence of sliding mode control:

$$0 \leq u_{1eq} \leq 1 \tag{11}$$

We observe that during the zero-crossings, for the case of unipolar control the equivalent control is at the limits, 0 or 1, but for the bipolar control the equivalent control is far from these limits, and regulation is possible without the risk of losing control over the current.

4. Experimental results

The active power filter presented in Fig. 2 was implemented, with the electrical parameters presented in Table 1.

Table 1

Electrical parameters

Parameter	Value
V_S	110 Vrms
f_S	50 Hz
L	4.2 mH
C	1500 μF
V_C	200 V
R_O	55 Ω
C_O	660 μF
R_S	7.5 Ω

The nonlinear load comprises a series resistor R_S followed by a diode rectifier with a load R_0-C_0.

The active power filters inverter bridge consists of four IGBT's with anti-parallel diodes.

Three signals are collected from the power circuit: the line current i_S, the line voltage v_S and the capacitor voltage v_C and fed to the control circuit, which offers the four driving signals for the inverter switches u_1-u_4.

The control circuit was implemented using a DSPACE 1104 controller board, with a TMS320F240 DSP and operated at a sampling frequency of 50 kHz.

The capacitor voltage v_C is filtered through a low-pass filter with a cut-off frequency of 80 Hz in order to reduce the unnecessary ripple and then compared to the reference voltage. The resulting error represents the input of the PI regulator and the computed output represents the factor k in (1).

The line voltage v_S is filtered through a band-pass filter with a center frequency of 50 Hz and a band-width of 5 Hz, which reduces significantly the distortions of the line voltage. It is then multiplied with the factor k and the result represents the reference current.

The actual line current i_S is compared with the reference current and sign of the error determines the driving signals u_1 and u_2 for the switches S1 an S2 of the inverter.

The signals v_S and u_1 determine together with the threshold voltage V_P if the inverter is controlled in bipolar or unipolar mode, by means of a simple logic.

Fig. 3 shows the voltage supplied by the grid v_S and the current i_L absorbed by the nonlinear load.

We observe that the supply voltage is not sinusoidal, having a THD of 3,2%. The THD of the load current was measured to be 55%. According to (1), the desired line current will be proportional to v_S and thus a distortion of the latter will lead from the start to a distortion in the line current. In order to avoid this consequence, the sensor tapped supply voltage was first filtered with a second order band-pass filter with a center frequency of 50 Hz and band of 5 Hz. Due to the characteristics of the filter no phase shift occurs at the center frequency.

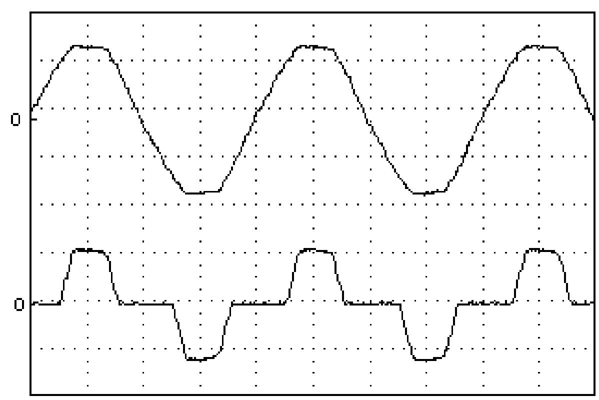

Fig. 3. Supply voltage v_S (up, 100V/div) and current absorbed by the nonlinear load i_L (down, 4A/div) (time: 5ms/div)

Also the zero crossings of the line current were corrected, according to the method presented in Section 2. Fig. 4 shows the supply voltage and the line current obtained with the method presented in [1], in phase but of the same shape as the supply voltage, with a THD of 5,9%. Fig. 5 shows supply voltage and the line current with the improvements proposed above. Besides synchronization with the supply voltage (power factor of 0,99), the line current has a sinusoidal shape and the zero crossings are improved. The THD obtained for i_S is 4,8%.

Fig. 6 shows the current absorbed by the active power filter i_F and the resulting line current i_S.

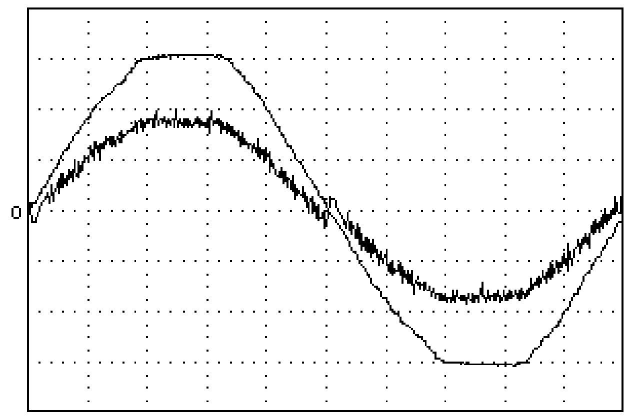

Fig. 4. Grid supply voltage v_S (50V/div) and line current i_S (2A/div) obtained according to [1] (time: 2ms/div)

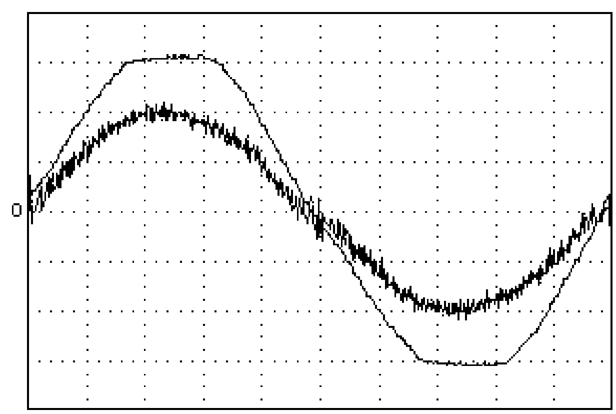

Fig. 5. Grid supply voltage v_S (50V/div) and line current i_S (2A/div) obtained according to obtained with proposed method (2ms/div), (time: 2ms/div)

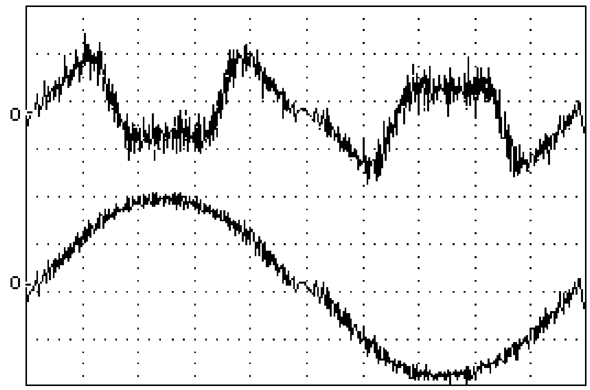

Fig. 6. Filter current i_F (up) and line current i_S (down) (time: 2ms/div)

Regarding the dynamic behavior, the response of the active power filter is influenced by the parameters of the PI regulator in the d.c.-voltage control loop. The proportional gain k_P dictates the reaction speed to load variations and therefore a big value would be desirable, but on the other side, a too big k_P would determine a great variation of the PI regulator output during a supply voltage cycle, which will lead to distortions in the reference current and consequently in the line current i_S. A set of experiments were made in order to establish how far k_P can be increased without degrading the THD of the line current with more than 1%, keeping the time constant of the PI regulator constant at τ=0,05 . Table 2 shows the results.

Table 2

Influence of proportionality gain k_P on the THD of i_S

k_P	1	2	3	4	5	6	7	7,3	8	9
THD i_S (%)	4.7	4.8	4.8	4.9	5,0	5,2	5,6	5,7	6.2	6,9

Fig. 7 and Fig. 8 show the dynamic behavior of the system from R_O=110Ω to R_O=55Ω, with k_P =1 and with k_P =7,3 correspondingly. We observe a significant improvement of the dynamic response which greatly compensates the small increase in the steady state THD of the line current.

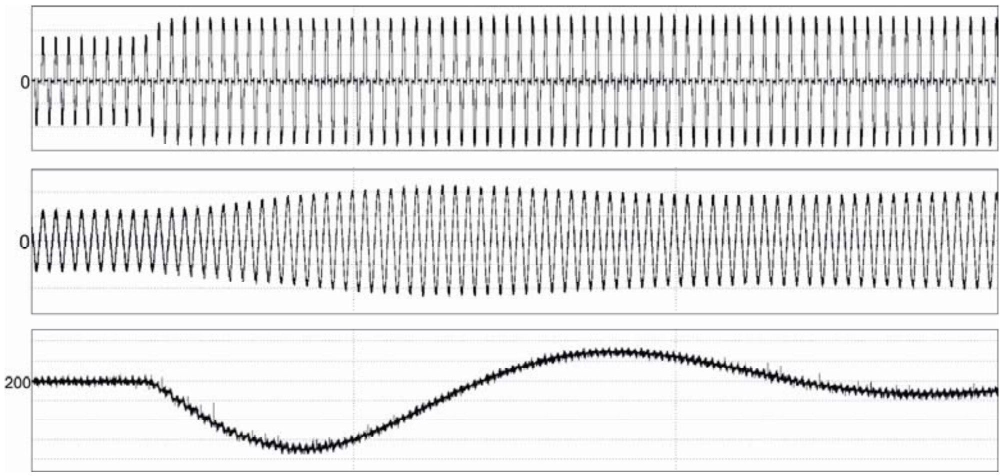

Fig. 7. Response to load step change for k_P =1. Load current i_L (up, 2A/div), line current i_S (middle, 2A/div) and capacitor voltage v_C (down, 5V/div) (time: 0,5s/div)

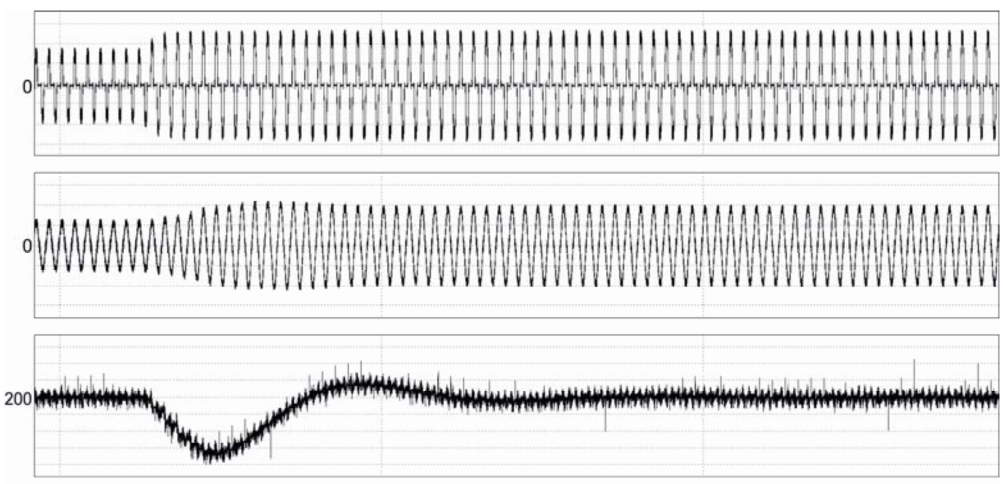

Fig. 8. Response to load step change for k_P =1. Load current i_L (up, 2A/div), line current i_S (middle, 2A/div) and capacitor voltage v_C (down, 2V/div) (time: 0,5s/div)

5. Conclusion

A single-phase shunt active power filter was presented and experimented. Sliding mode control was analyzed and the equivalent control was presented for both operating modes. The distorting effects of the non-sinusoidal supply voltage on the filtered line current were eliminated and the zero-crossings of the line current were corrected by changing the operation mode of the inverter from unipolar to bipolar operation during certain intervals. The dynamic behavior was analyzed and an advantageous balance between a good dynamic response and a low THD for the line current was achieved. The load current THD of 55% was reduced to 5,8% for the line current.

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