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SIMULATION AND REAL TIME IMPLEMENTATION OF THREE PHASE FOUR WIRE SHUNT ACTIVE POWER FILTER BASED ON SLIDING MODE CONTROLLER

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Key words: Active power filter (APF), Four wire system, Power quality, Sliding-mode controller (SMC), Self-tuning filter.

Harmonic current suppression and semiconductors protection depend greatly on the stability of dc side voltage of the inverter. This paper presents a simulation and experimental study of a three-phase four wire shunt active power filter based on two level voltage source inverter. The study is focused on dc bus voltage control where it is proposed to use sliding mode controller that provides higher performance and better robustness. Therefore, the main motivation of this work is to find a suitable and efficient control algorithm to obtain a lower total harmonic distortion (THD) and better compensation. The algorithm that is used in identifying the reference currents is based on p_q theory improved by self-tuning filter. This latter has a perfect ability in harmonic currents extraction. To prove the effectiveness of proposed system, simulation and real time implementation of the developed algorithms were conducted using Matlab/Simulink and experimental platform. The obtained results demonstrate that the employment of this technique enhances the performance of active filter in harmonic current suppression and semiconductors protection.

1. INTRODUCTION

Nonlinear loads such as power electronics devices are the main source of harmonic currents in a distribution system. The presence of these harmonic components can lead to power factor deterioration, and the presence of neutral unbalanced currents. However, active filters were widely used and applied for harmonic current suppression and power factor correction [1–7].

A traditional three-phase three-wire APF is not suitable for harmonics elimination in the neutral wire. Recently many harmonic control techniques were presented and studied to improve the performance of three phase four wire active power filter used for unbalanced loads [2, 4, 7]. The main advantages of these techniques are: a high computation rate, a high robustness and ability for adaptation. Harmonic current suppression and semiconductors protection depend greatly on the stability of dc side voltage of voltage source inverter (VSI). Thus, the control of inverter dc voltage is necessary to keep its value constant and limit the fluctuations in order to prevent semiconductors from failure.

The control of dc voltage of active power filter (APF) is a hot issue, and several controllers were studies in previous researches [6–10]. Many research works have been conducted on the application of sliding mode control to improve the dynamic behavior of the compensation system [11–13]. Moreover, a number of hybrid controllers were also designed to ensure the stability and to reduce the parameters fluctuations by combining sliding mode control with other techniques [7, 11]. Recently, the intelligent controllers were used to replace the conventional proportional integral (PI) that is used to control the dc capacitor voltage of shunt active power filter since a long time [4–12].

In intelligent controllers, the algorithm of tracking the reference value of dc bus voltage is based on human expertise. While, the mathematical model of the system is not required. However, sliding mode control (SMC) was extensively studied and investigated over the past decades [13–18]. This strategy provides a higher robustness and better efficiency. Therefore, the main advantage of this strategy is solving the problem of system instability under parameters variation and disturbances. SMC is also suitable for converter switches with their intrinsic non-linearity ensuring perfect stability in any operating condition.

In this paper, SMC is proposed for dc bus voltage control of three phase three wire SAPF. Self tuning filter is suggested to improve the performance of p-q theory and provides better identification. The simulation is performed using Matlab/Simulink and then is investigated in experimental test bench based on Dspace board 1 104. The simulation and experimental results demonstrate the capability of the system in power quality improvement and the prevention of system reliability.

2. SHUNT ACTIVE FILTER CONFIGURATION

The basic configuration of three phase four wire APF is illustrated in Fig. 1. In this topology, the inverter comprises four arms consisting of eight insulated gate bipolar transistor (IGBT) switches. This configuration has been proposed in order to avoid the use of the three-leg split-capacitor topology such as that presented in [19], and also the fourth leg is used to stabilize and control the neutral current of the system.

Four-wire-SAPF topology always gives better results because the four leg of the inverter are used to control the three phase currents as well as the neutral current. On the other hand, the three-wire topology of APF with split-capacitor directly controls only three currents and the fourth is the result of three phase balanced system equation.

The purpose of the APF is to compensate harmonics, reactive power, neutral current and unbalanced current that are created by non-linear loads represented by single phase rectifiers. For which, the main power supply provides only sinusoidal balanced three-phase currents with unity power-factor. Voltage source inverter (VSI) takes the role of generating the necessary current to eliminate harmonic, reactive

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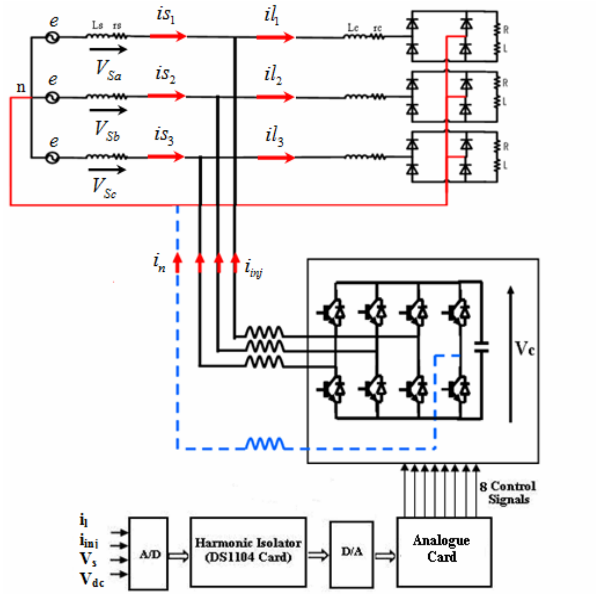

Fig. 1 – Three-phase four-wire shunt active filter.

and unbalanced currents as well as the current in neutral wire. The dc side of VSI is regulated using sliding mode controller which gives the reference value of active power. This latter is used to control the VSI based on p_q theory as described in the next section.

3. REFERENCE CURRENT CALCULATION

3.1. SELF TUNING FILTER

M. Abdusalam *et al.* [20] are proposed to use multivariable filter called self tuning filter (STF) in harmonic extraction as shown in Fig. 2. Its operation principle is based on the following equations (1,2) :

$$\hat{x}_\alpha(s) = \frac{k}{s}\left[x_\alpha(s) - \hat{x}_\alpha(s)\right] - \frac{w_c}{s}\hat{x}_\beta(s) \qquad (1)$$

$$\hat{x}_\beta(s) = \frac{k}{s}\left[x_\beta(s) - \hat{x}_\beta(s)\right] + \frac{w_c}{s}\hat{x}_\alpha(s) \qquad (2)$$

where $x_\alpha(s)$, $x_\beta(s)$ are the input current or voltage signals, $\hat{x}_\alpha(s)$ and $\hat{x}_\beta(s)$ are the output current or a voltage signals and finally w_c is the pulsation of STF, as one can see it in Fig. 2, whereas, k is an adaptive gain. It is adjusted by experiment to provide faster response and to increase the selectivity of the filter.

The authors in [20] tested the selectivity of STF by varying the gain k, they observed that small variation of this gain influences the filter selectivity.

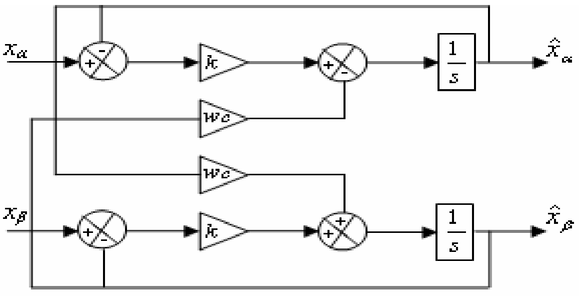

Fig. 2 – Self-tuning filter tuned to the pulsation wc.

3.2. HARMONIC CURRENTS IDENTIFICATION

Numerous techniques were suggested for extracting the harmonic currents [4, 5]. Among them are techniques that base on frequency domain. They use the fast Fourier transformation (FFT) to identify the harmonic components. However, many algorithms that bases on time domain were suggested in literature. Therefore, the instantaneous p-q theory is the most common one. It bases on instantaneous power computation in the time domain. In the present research, the STF is proposed to replace the conventional high pass filter in p–q method. The block scheme of the proposed algorithm, p-q theory based on STF is clarified in Fig. 3.

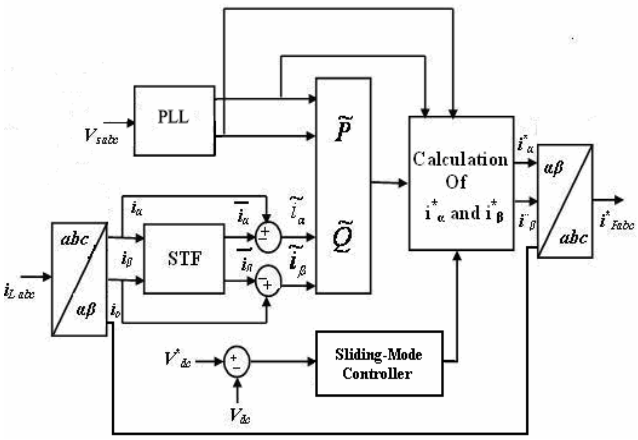

Fig. 3 – Block diagram of p-q algorithm based on STF- harmonic isolator.

The reference currents (harmonic currents) extraction is based on α-β-o transformation to obtain real and imaginary powers. The voltages (V_{Sa}, V_{Sb} and V_{Sc}) and currents (I_{La}, I_{Lb} and I_{Lc}) are transformed into Two-phase system according to the following equation (3):

$$\begin{bmatrix} x_\alpha \\ x_\beta \\ x_o \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{pmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \\ \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{pmatrix} \begin{bmatrix} x_a \\ x_b \\ x_c \end{bmatrix}. \qquad (3)$$

After that, the harmonic components of the current are extracted by STF that saves only the fundamental component $(\bar{i}_\alpha, \bar{i}_\beta)$. Then, the ac components of source current is obtained by subtracting the input signals of STF from the corresponding output signals. The obtained signals $(\tilde{i}_\alpha, \tilde{i}_\beta)$ represent the harmonic currents consumed by the load in stationary reference frame.

Phase-locked loop (PLL) is used to export phase and frequency information of source voltage that allows obtaining sine and cosine signals, these signals are used to retrieve the sinusoidal waveform of the main voltage. This technique bases in Clarke transformation of the sensed three-phase source voltage (V_{Sa}, V_{Sb} and V_{Sc}) from *a-b-c* coordinates to the d-q coordinates.

The obtained source voltage components in stationary frame are used to calculate source powers as follows:

$$\begin{bmatrix} p \\ q \end{bmatrix} = \begin{pmatrix} \hat{v}_\alpha & \hat{v}_\beta \\ -\hat{v}_\beta & \hat{v}_\alpha \end{pmatrix} \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix}. \qquad (4)$$

The last equation represents the instantaneous powers of the source which include fundamental and harmonic components. However, alternative component of powers is needed for obtaining the reference currents that are necessary for compensation as given in (5).

$$\begin{bmatrix} \tilde{i}_\alpha \\ \tilde{i}_\beta \end{bmatrix} = \frac{1}{\hat{v}_\alpha{}^2 + \hat{v}_\beta{}^2} \begin{pmatrix} \hat{v}_\alpha & -\hat{v}_\beta \\ \hat{v}_\beta & \hat{v}_\alpha \end{pmatrix} \begin{bmatrix} \tilde{p} \\ \tilde{q} \end{bmatrix}. \qquad (5)$$

The alternative component of active power is achieved after adding the active power needed for dc side voltage regulation P_c as illustrated in Fig. 3.

Then, the reference currents of the filter in the *a–b–c* coordinates are given by (6):

$$\begin{bmatrix} \tilde{i}_{f\,a} \\ \tilde{i}_{f\,b} \\ \tilde{i}_{f\,c} \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & 0 \\ \frac{1}{2} & \frac{\sqrt{3}}{2} \\ -\frac{1}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} \tilde{i}_\alpha \\ \tilde{i}_\beta \end{bmatrix} \qquad (6)$$

4. DC BUS VOLTAGE CONTROL

The average voltage of the capacitor (V_{dc}) has to be maintained at a fixed value. The main cause of its variation is the active filter losses (switches and output filter). The control of the energy stored in the capacitor must be done by the adjusting the reference currents of the main source.

The output of sliding mode controller P_c is added to the distorted active power $\tilde{p}$ giving an active fundamental current that corrects Vdc. The power P_c represents the active power required to maintain dc voltage equal to the desired value (V^*_{dc}). Different control algorithms were applied to regulate the dc bus voltage. In this section, the dc capacitor voltage is regulated using the sliding mode controller (SMC).

A simple form of control action using sliding-mode theory is a relay function Fig. 4, which is given by (7):

$$u_n = k_c \operatorname{sign}(s(x)) \qquad (7)$$

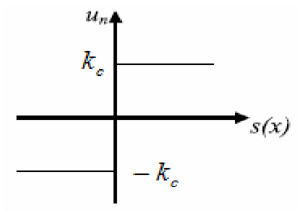

Fig. 4 – Relay function.

In this context, the stability of the sliding surface can be verified using the Lyapunov theorem. The following positive function ($v(x)$> 0) is chosen such that:

$$v(x) = \frac{1}{2} s^2(x) \qquad (8)$$

Its derivative is given by:

$$v'(x) = s'(x).s(x) \qquad (9)$$

The sliding surface $s(x)$ is given by the error between dc bus voltage and its reference as in (10). While the control signal u_n represents the power p_c required to maintain the dc bus voltage at a fixed value.

$$s(x) = V^*_{dc} - V_{dc} = \sigma_c \qquad (10)$$

$$u_n = p_c \qquad (11)$$

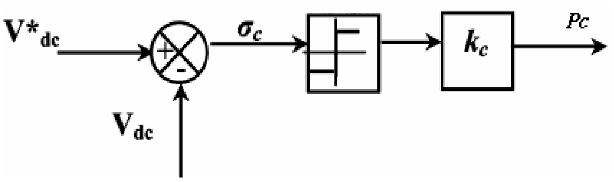

Fig. 5 – Block diagram of sliding mode controller.

5. SIMULATION AND EXPERIMENT RESULTS

To evaluate the performance of proposed system, simulation study is carried out based on Matlab/Simulink and Simpower system. Also, an experimental platform has been developed in laboratory to validate and to confirm the simulation results as depicted in Fig. 6. The real-time implementation on the dSPACE DS1104 is carried out using real-time interface in MATLAB/Simulink environment. This experimental test bench is composed mainly from the following elements:

– The three-phase four-wire shunt active power filter is made up using three-phase IGBTs of 1200 V and 50 A (SKM 50 GB 123D, SEMIKRON).

– A dSPACE 1104 card (controller board) was integrated in a computer that allows generating the required pulses to control the inverter switches.

– Voltage sensors HAMEG (HZ64).

– Current sensors (hall-effect sensor LEM PR30).

The visualization of system waveforms is performed through oscilloscope.

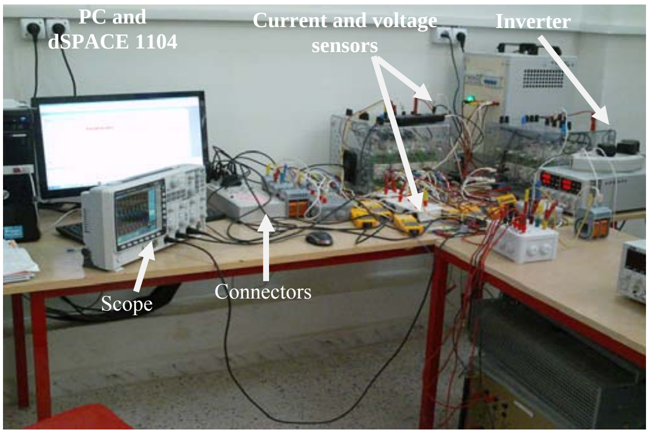

Fig. 6 – Experimental test bench.

Three phase power supply is connected by three balanced loads based on single phase diode rectifier. The experimental and simulation parameters of the system are given in Table 1 in Appendix section. The effectiveness of the proposed system and the robustness of the SMC are studied using simulation and experiment for different operating modes.

The simulation and experimental results are shown in the Figs. 6 to 19. In the previous figures, the measured parameters with and without filter connection are given.

Figures 7 and 11 show the simulated and experimental source current frequency spectrum without filter respectively. It can be observed that the THD (total harmonic distortion) is too high and equal to 22.95 % according to simulated spectrum. While Figs. 15 and 18 represent the frequency spectrum of source current after filtering which has been reduced to 2.14 % confirming IEEE 519-1992.

Otherwise, Figs. 8 and 12 illustrate the simulated and experimental neutral current waveform in A without filter respectively. It is noticed that the neutral current is different to zero. While, this current is deleted after injecting the filter as shown in Figs. 16 and 19 . Which demonstrate the capability of proposed algorithm in neutral current suppression.

Figures 10 and 14 show the simulated and experimental source currents (i_{S1}, i_{S2}, i_{S3}) and source voltage V_{s1}. the obtained waveforms are relatively sinusoidal and the phase shift is deleted. The last results prove the effectiveness of four leg SAPF in harmonic current suppression and reactive power compensation.

In order to check the robustness of the sliding mode control, the value of the load at the output of the rectifier is changed from (R, L) to (R_2, L_2) at t = 0.012 s, as illustrated in Figs. 16 and 19. According to Figs. 17 and 20, it can be seen that the dc voltage can track the reference voltage rapidly with fast response proving the effectiveness of this control technique.

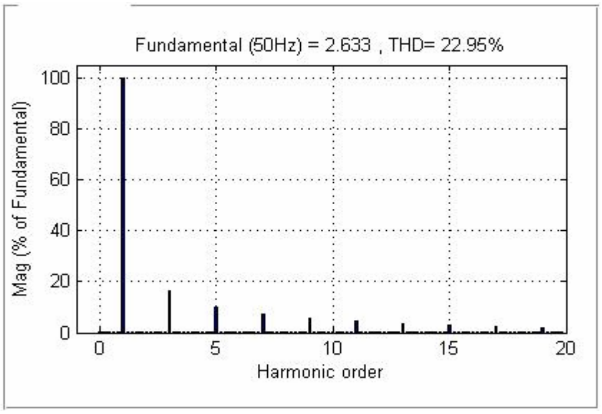

Fig. 7 – Simulated source current spectrum without filter (i_{s1}).

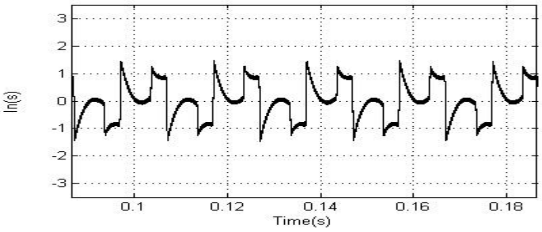

Fig. 8 – Simulated neutral current waveform in (A) without filter.

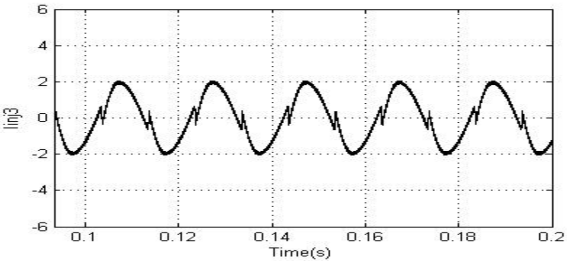

Fig. 9 – Simulated injected current i_F (A) waveform.

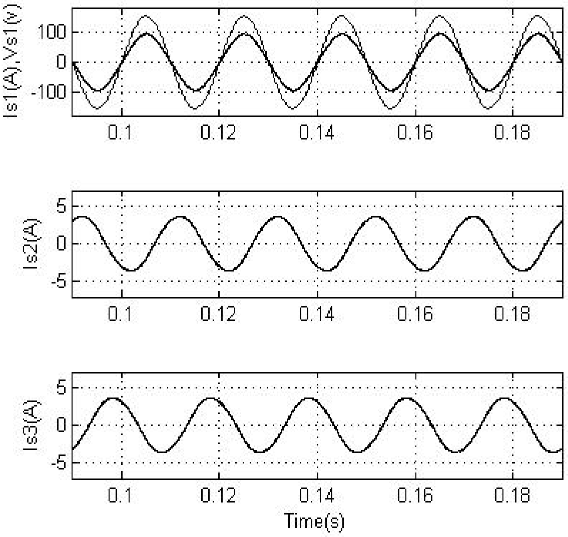

Fig. 10 – Simulated source current i_S (A) waveform.

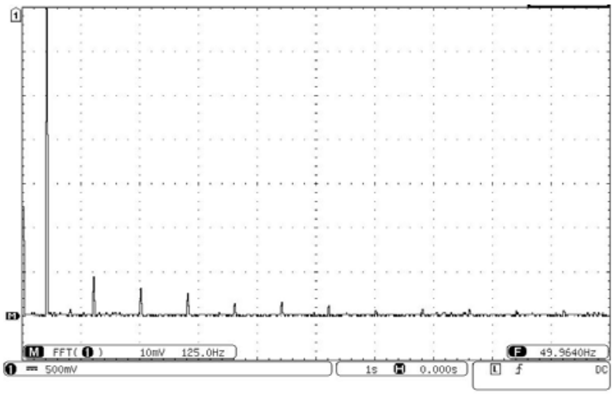

Fig. 11 – Experimental source current spectrum without filter.

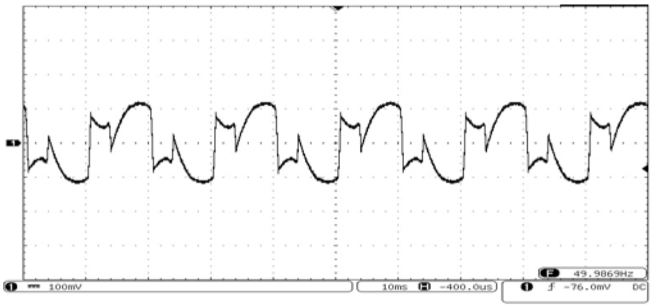

Fig. 12 – Experimental neutral current waveform in (A) without filter.

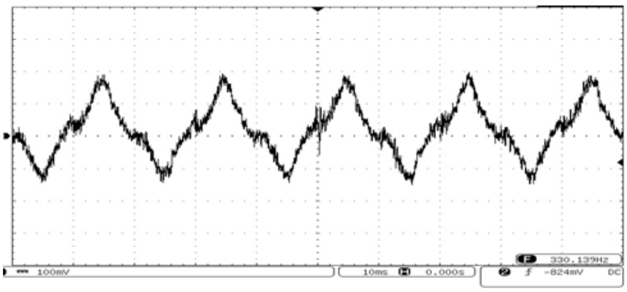

Fig. 13 – Experimental injected current i_F (A) waveform.

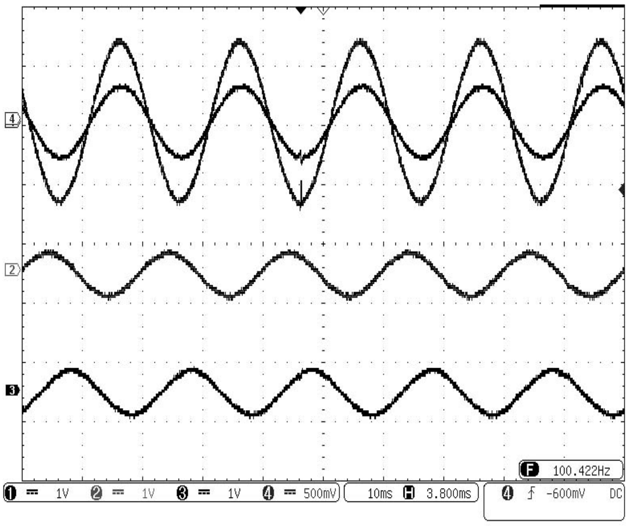

Fig. 14 – Experimental source current i_S (A) waveform.

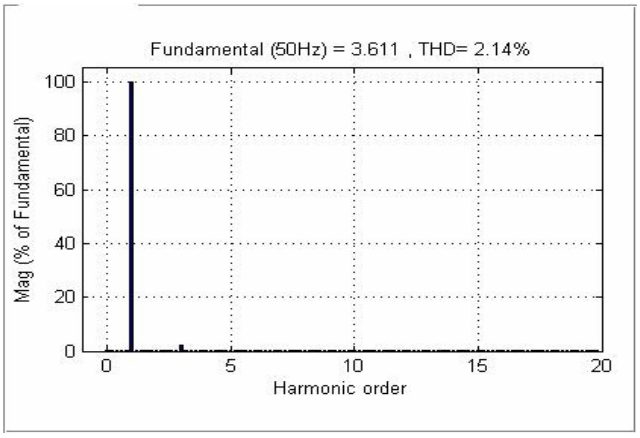

Fig. 15 – Simulated source current spectrum with filter.

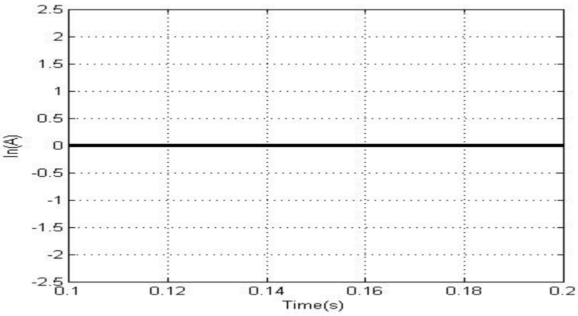

Fig. 16 – Simulated neutral current with filter in (A).

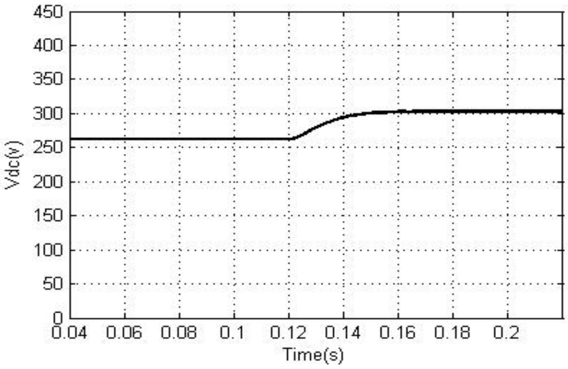

Fig. 17 – Simulated dc bus voltage.

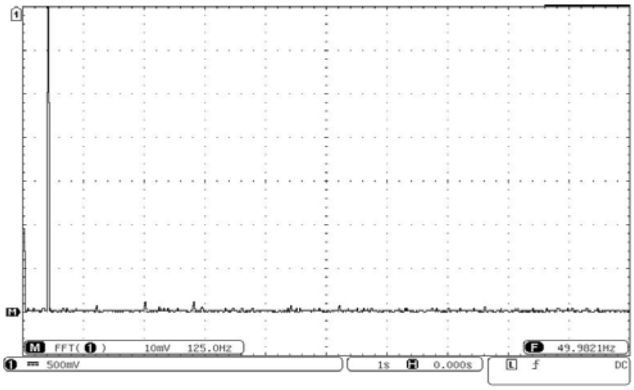

Fig. 18 – Experimental source current spectrum with filter.

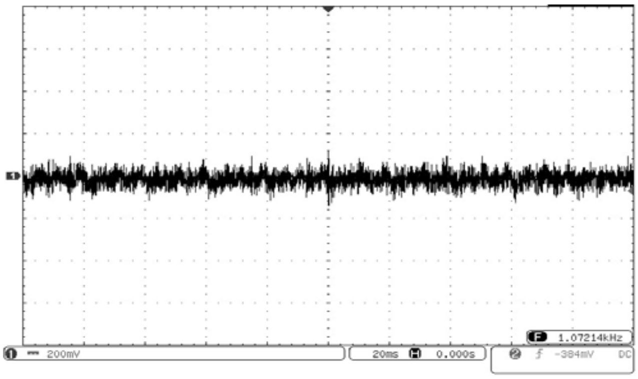

Fig. 19 – Experimental neutral current with filter in (A).

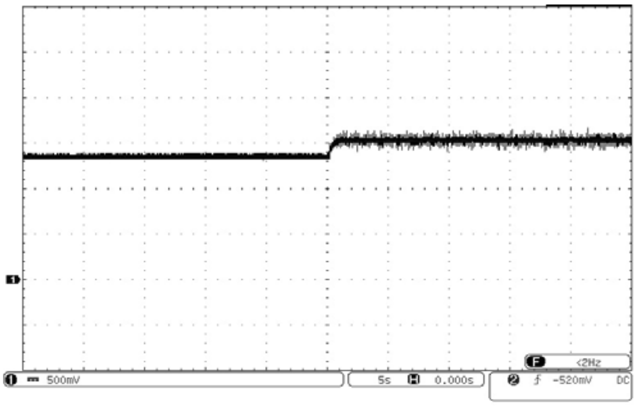

Fig. 20 – Experimental dc bus voltage.

6. CONCLUSIONS

In this paper, three phase four wire shunt active filter based on sliding mode controller is studied by simulation and experiment. To extract and filter undesired currents, p-q theory improved by STF is proposed. Simulation and experimental results in various cases demonstrate the efficiency and the effectiveness of the proposed algorithm in harmonic currents suppression and neutral current elimination as well as reactive power compensation. Sliding mode controller provides well performance and high robustness in dc bus voltage regulation. Therefore, the stabilization of dc side can give effective compensation of undesired currents where the THD is reduced to 2.14 %.

APPENDIX

Table 1

System parameters used in simulation

Source	V_s , f	110V, 50 Hz
	R_s , L_s	0.45Ω, 2.5 mH
Load	R, L	110Ω, 200 mH
	R_2, L_2	65Ω, 200 mH
Dc Link	V_{dc}	300V
	C_{dc}	2200 μF
SAPF	R_f,	0.5 Ω
	L_f	4 mH

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