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A Combined Sliding Mode Space vector Modulation Control of the Shunt Active Power Filter Using Robust Harmonic Extraction Method

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Abstract: This paper presents a combined sliding mode space vector modulation control of the shunt active power filter using robust harmonic extraction method to improve the power quality such as current harmonics and reactive power compensation due to the non-linear loads and unbalanced voltage source. To verify the validity of the analysis and the feasibility of the proposed control method a set of simulation tests have been conducted using Matlab/Simulink. A comparison between the conventional instantaneous powers method (PQ) used for harmonic extracting and the new PQ based on a multivariable extraction filter demonstrates the superiority of the proposed control scheme.

Keywords: Shunt Active Power Filter (SHAPF), Multivariable Filter (MVF), Space vector Modulation (SVM), Sliding Mode controller (SMC).

1. INTRODUCTION

In recent years, the increasing use of power electronic devices has led to the deterioration of power quality due to harmonic generations [1]. The terminology and the guidelines for power quality have been described in detail at IEEE-519 and IEC-555. According to these guidelines, the allowed total harmonic distortion should be less than 5% [2].

The aforementioned problems are partially solved with the help of passive filters [3-5]. However, this kind of filter cannot solve random variations in the load current waveform and voltage waveform. On the other hand, active filters such as Static Var Compensator (SVC), Shunt Active Power Filter (SHAPF), Series Active Power Filter (SAPF), and hybrid filters are proposed to ensure power quality [6].

SHAPFs are typically used for the elimination of current harmonics, for reactive power compensation, and in balancing unbalanced current. As current harmonics are included in the system under consideration, shunt active filters are connected to the load side [7,8].. To remove harmonics and the reactive components of nonlinear loads, these filters act as sources injecting different compensation currents whose harmonic and reactive components have equal amplitude but a phase difference of 180°. Moreover, these filters are often used as static generators to balance voltage profiles and improve voltage [9].

Different control approaches for the SHAPF have been proposed. In [10] authors have applied a linear control using PI controller. The control of the SHAPF connected to a Wind system by PI controller is proposed in [11]. An intelligent controller has been applied by [12] and [13]. A four wire topology of the SHAPF has been studied in [14], [15] and [16].

The aim of this paper is twofold. Firstly to design a sliding mode controller combined with space vector modulation for the SHAPF to enhance power quality. Secondly, to compare the performances of the proposed robust harmonic extraction method with the conventional instantaneous powers method (PQ theory) to validate the proposed control scheme, through an extensive simulation results for a passive load connected through an uncontrolled bridge rectifier.

The rest of the paper is organized as follows: in section II, the control design of the SHAPF is presented, while in section III, simulation results and their discussion are given, finally a conclusion of the present work is derived.

2. CONTROL DESIGN

The basic operation of the proposed control method associated to a nonlinear load is shown in Fig. 1. The switch control signals are derived from a Space Vector Modulator (SVM). Voltage references for the SVM are derived from the sliding mode controllers. The references are computed by using the instantaneous PQ theory [17-19]. The compensation objective is to compensate current harmonics, reactive power, and to regulate the DC bus voltage. Detailed description of different parts of SHAPF is given hereafter.

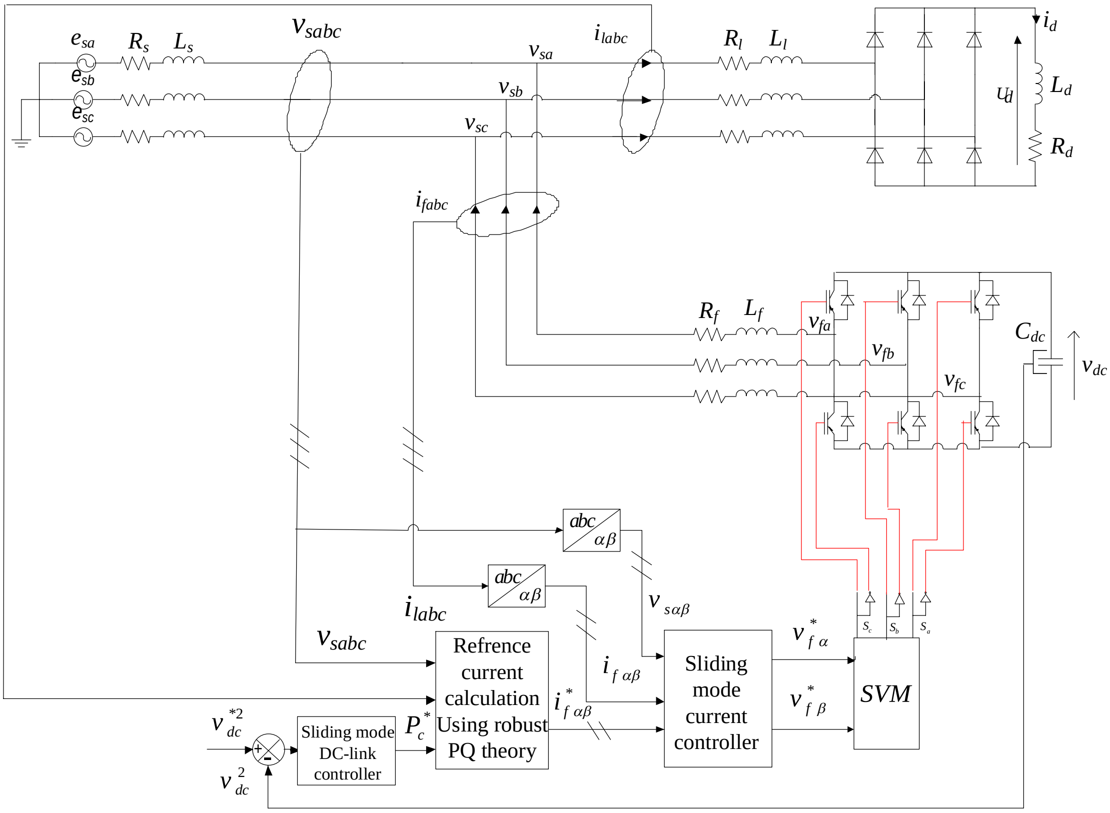

Fig. 1. Sliding mode control scheme of the SHAPF.

Mathematical Model of SHAPF

The differential equations describing the dynamic model of SHAPF are defined in stationary α-β reference frame.

The SHAPF's model is governed by the following equation.

$$\dot{x} = f(x) + g(x)u \tag{1}$$

where:

$$f(x) = \begin{bmatrix} -\frac{R_f}{L_f} i_{f p\alpha} - \frac{v_{s\alpha}}{L_f} \\ -\frac{R_f}{L_f} i_{f p\beta} - \frac{v_{s\beta}}{L_f} \end{bmatrix}, g(x) = \begin{bmatrix} \frac{1}{L_f} & 0 \\ 0 & \frac{1}{L_f} \end{bmatrix}, x = \begin{bmatrix} i_{f\alpha} \\ i_{f\beta} \end{bmatrix}, u = \begin{bmatrix} v_{f\alpha} \\ v_{f\beta} \end{bmatrix}$$

and $v_{s\alpha\beta}$ are the voltages of the source in the α-β coordinates, $i_{f\alpha\beta}$ and $v_{f\alpha\beta}$ are the α-β axis currents of the filter.

Harmonic extraction

Active filter depends greatly on the extraction method used to eliminate harmonics from the distorted waveforms [10], [19]. Hereafter, harmonics extraction methods are described.

A. Harmonic currents extraction using conventional PQ theory

The algorithm of the instantaneous powers theory is highlighted in Fig. 2.
Instantaneous active and reactive powers of the nonlinear load are calculated by:

$$\begin{bmatrix} P_l \\ Q_l \end{bmatrix} = \begin{bmatrix} v_{s\alpha} & v_{s\beta} \\ v_{s\beta} & -v_{s\alpha} \end{bmatrix} \begin{bmatrix} i_{l\alpha} \\ i_{l\beta} \end{bmatrix} \tag{2}$$

Where the instantaneous powers can be expressed as follows:

$$\begin{cases} P_l = \bar{P}_l + \tilde{P}_l \\ Q_l = \bar{Q}_l + \tilde{Q}_l \end{cases} \tag{3}$$

DC values ($\bar{P}_l$,$\bar{Q}_l$) of P_l and Q_l are average active and reactive power originating from the positive-sequence component of the nonlinear load current. AC values ($\tilde{P}_l$,$\tilde{Q}_l$) of P_l and Q_l are the ripple active and reactive powers.

For harmonic and reactive power compensation, all of the reactive power ($\bar{Q}_l$ and $\tilde{Q}_l$ components) and harmonic component ($\tilde{P}_l$) of active power are selected as compensation power references and the compensation currents reference are calculated as (4).

$$\begin{bmatrix} i^*_{f\alpha} \\ i^*_{f\beta} \end{bmatrix} = \frac{1}{v^2_{s\alpha} + v^2_{s\beta}} \begin{bmatrix} v_{s\alpha} & v_{s\beta} \\ v_{s\beta} & -v_{s\alpha} \end{bmatrix} \begin{bmatrix} \tilde{P}_l \\ Q_l \end{bmatrix} \tag{4}$$

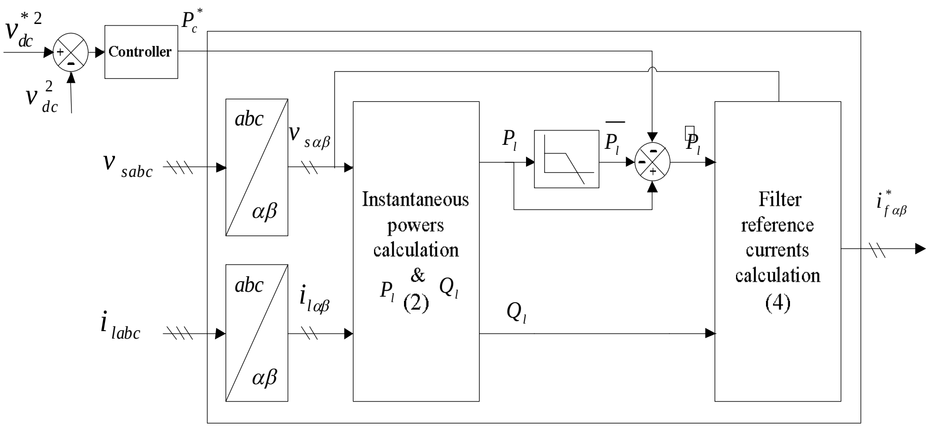

Fig. 2. Harmonic currents extraction scheme using PQ theory.

On the other hand the signal P^*_c is used as an average real power, and is obtained from the DC voltage controller.

B. Harmonic currents extraction using PQ theory based on Multivariable filter

a- Multivariable filter

The multivariable filter (Fig. 3) is designed to extract the fundamental component of electrical signals (voltage or current) directly in the αβ axes. The transfer function is obtained from the integration of the synchronous reference. The transfer function is defined as [20]:

$$\bar{X}_\alpha(s) = \frac{k}{s}[X_\alpha(s) - \bar{X}_\alpha(s)] - \frac{\omega}{s}\bar{X}_\beta(s)$$
$$\bar{X}_\beta(s) = \frac{k}{s}[X_\beta(s) - \bar{X}_\beta(s)] + \frac{\omega}{s}\bar{X}_\alpha(s) \quad (5)$$

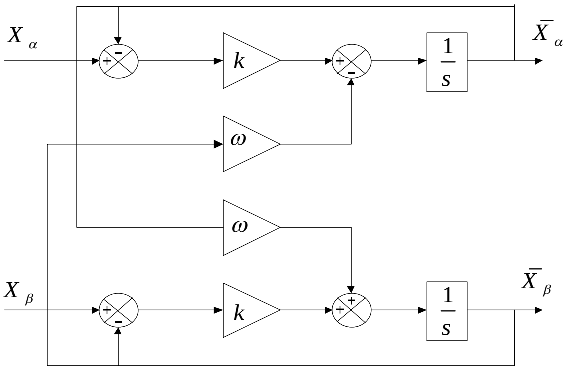

Fig. 3. Harmonic currents extraction scheme using PQ theory.

Finally the robust PQ theory algorithm is shown in Fig. 4.

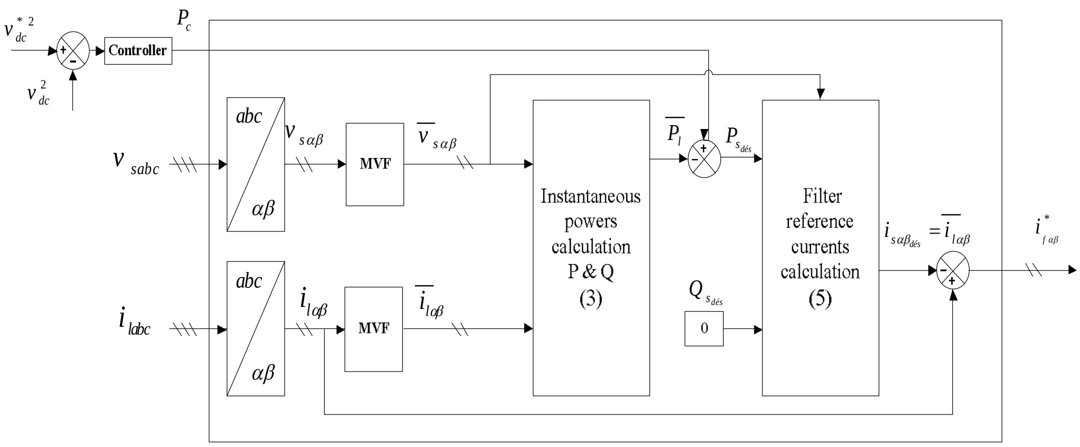

Fig. 4. Harmonic currents extraction scheme using PQ theory.

Sliding Mode Controller (SMC) Synthesis

Consider the nonlinear system represented by:

$$\dot{x} = f(x) + g(x)u \quad (6)$$

where *g(x)* and *f(x)* are scalar functions.

The well-known method to form the sliding control law of the previous system is shown in Fig. 5 [21]. It consists of combination between the equivalent control u_{eq} with the switching part u_s, as follows:

$$u = u_{eq} + u_s \quad (7)$$

u_{eq} and u_s can be calculated as follows [22]:

$$u_{eq} = g(x)^{-1}(-f(x) + \dot{x}^*) \quad (8)$$

$$u_s = U_{\max}\,\mathrm{sgn}(S(x)) \quad (9)$$

Where sgn is the sign function, U_{max} is a positive constant and *S(x)* is the sliding surface.

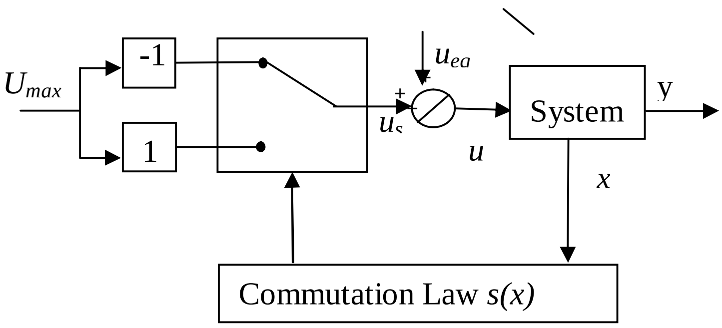

Fig. 5. Adopted sliding mode controller scheme.

A. Currents SMC synthesis

The sliding surfaces are chosen as follows:

$$\begin{aligned} S_1 &= \lambda_1 (i_{f\alpha} - i^*_{f\alpha}) \\ S_2 &= \lambda_2 (i_{f\beta} - i^*_{f\beta}) \end{aligned} \qquad (10)$$

The equivalent control takes the following form:

$$u_{eq} = g(x)^{-1}(-f(x) + \dot{x}^*) \qquad (11)$$

The switching control law is designed as follows:

$$u_s = -U_{\max}\ sign(S) \qquad (12)$$

where:

$S = \begin{bmatrix} S_1 \\ S_2 \end{bmatrix}, \ U_{\max} = \begin{bmatrix} U_{\max 1} \\ U_{\max 2} \end{bmatrix}$

Finally, the control law is given by:

$$\begin{cases} v^*_{f\alpha} = R_f i_{f\alpha} + v_{s\alpha} + L_f \dot{i}^*_{f\alpha} - U_{\max 1} sign(S_1) \\ v^*_{f\beta} = R_f i_{f\beta} + v_{s\beta} + L_f \dot{i}^*_{f\beta} - U_{\max 2} sign(S_2) \end{cases} \qquad (13)$$

where, U_{max1} ,U_{max2} are positive constants.

B. DC voltage SMC synthesis

The sliding surface is chosen as follows:

$$S_{dc} = \lambda_{dc} e_{vdc} \qquad (14)$$

where:

$e_{vdc} = v^2_{dc} - v^{*2}_{dc}$

The control law is given by the following linear feedback with switching functions.

$$P^*_c = c_1 e_{vdc} y_1 + c_2 \dot{e}_{vdc} y_2 \qquad (15)$$

Where, c_1 and c_2 are positive constants, and the switching functions y_1 and y_2 are given by [23]:

$$y_1 = \begin{cases} 1 & si \quad S_{dc} e_{vdc} > 0 \\ -1 & si \quad S_{dc} e_{vdc} < 0 \end{cases} \text{ and } y_2 = \begin{cases} 1 & si \quad S_{dc} \dot{e}_{vdc} > 0 \\ -1 & si \quad S_{dc} \dot{e}_{vdc} < 0 \end{cases} \qquad (16)$$

Space Vector Modulation

In this section, SVM technique is presented to produce PWM control signals (s_a, s_b and s_c) to the power switches of the inverter. SVM compensates the required volt-seconds using discrete switching states and their on-times. The space vector diagram of a three phase voltage source inverter is a hexagon (Fig. 6), consisting of six sectors. Every sector is an equilateral triangle of a height h =√3/2 [24]. For any given reference vector, the sector of operation is determined by using Eq (17).

$$S_i = \mathrm{int}\left(\frac{\theta_s}{60}\right) + 1 \tag{17}$$

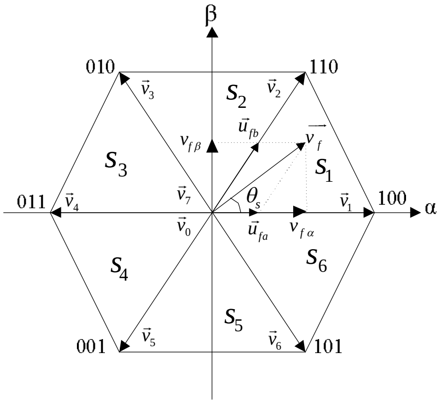

Fig. 6. Space vector diagram.

The on-time calculation is similar for all sectors. Volt-second equation is given by:

$$\overrightarrow{v_f} T_s = t_i \vec{v}_i + t_{i+1}\vec{v}_{i+1} + t_0 \vec{v}_0 \tag{18}$$

where $T_s = 1/f_s$, with fs is the switching frequency.
In the first sector,

$$\begin{cases} \vec{v}_1 = \sqrt{\frac{2}{3}} v_{dc} \\ \vec{v}_2 = \sqrt{\frac{2}{3}} v_{dc} \left(\frac{1}{2} + j\,\frac{\sqrt{3}}{2}\right) \\ \vec{v}_0 = 0 \end{cases} \tag{19}$$

The reference vector can be also written as follows,

$$\overrightarrow{v_f} = v_{f\alpha} + j v_{f\beta} \tag{20}$$

From Equations (18, 19 and 20) one can find:

$$\begin{cases} v_{f\alpha} = \sqrt{\frac{2}{3}} v_{dc} \frac{t_1}{T_s} + \frac{1}{\sqrt{6}} v_{dc} \frac{t_2}{T_s} \\ v_{f\beta} = \frac{1}{\sqrt{2}} v_{dc} \frac{t_2}{T_s} \end{cases} \tag{21}$$

From equation (21), ON times calculation are given below

$$\begin{cases} t_1 = \dfrac{\sqrt{6} v_{f\alpha} - \sqrt{2} v_{f\beta}}{v_{dc}} T_s \\ t_2 = \dfrac{\sqrt{2} v_{f\beta}}{v_{dc}} T_s \\ t_0 = T_s - (t_1 + t_2) \end{cases} \tag{22}$$

The choice of the null vector determines the SVM scheme. There are a few options: the null vector v0 only, the null vector v7 only, or a combination of the null vectors. A popular SVM technique is to alternate the null vector in each cycle and to reverse the sequence after each null vector as shown in Fig. 7. This will be referred to as the symmetric 7-segment technique [25].

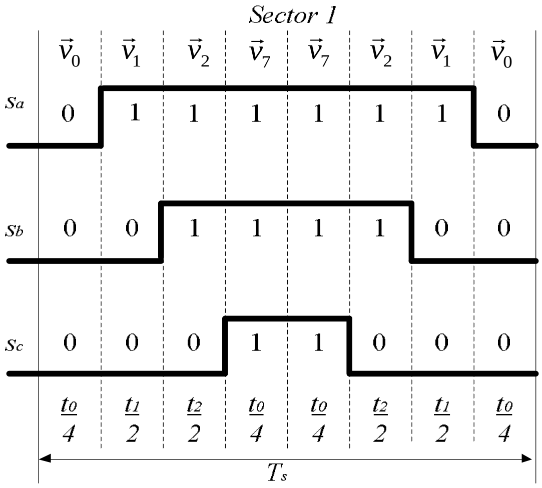

Fig. 7. 7-Segment Switching Sequence for Vref in sector 1.

3. SIMULATION RESULTS AND DISCUSSION

Harmonic current filtering, reactive power compensation and performance of the SHAPF with the proposed control have been examined in Matlab/Simulink environment, under nonlinear load variation and voltage sag. The parameters used in the present study are shown in Table 1.

Table1 System parameters

Parameter	value
RMS value of the source voltage	220 V
DC-link capacitor C_{dc}	8 mF
Source impedance R_s, L_s	3mΩ, 2.6 µH
Shunt filter impedance R_f, L_f	20 mΩ, 2.5 mH
Line impedance R_l, L_l	10 mΩ, 0.3 µH
Diode rectifier load R_d , L_d	15 Ω, 2 mH
DC-link voltage reference	900 V
Switching frequency f_s	12 kHz
$\lambda_1 = \lambda_2 = \lambda_{dc}$	1
$U_{max1} = U_{max2}$,	840
c_1,c_2	0.3, 0.08

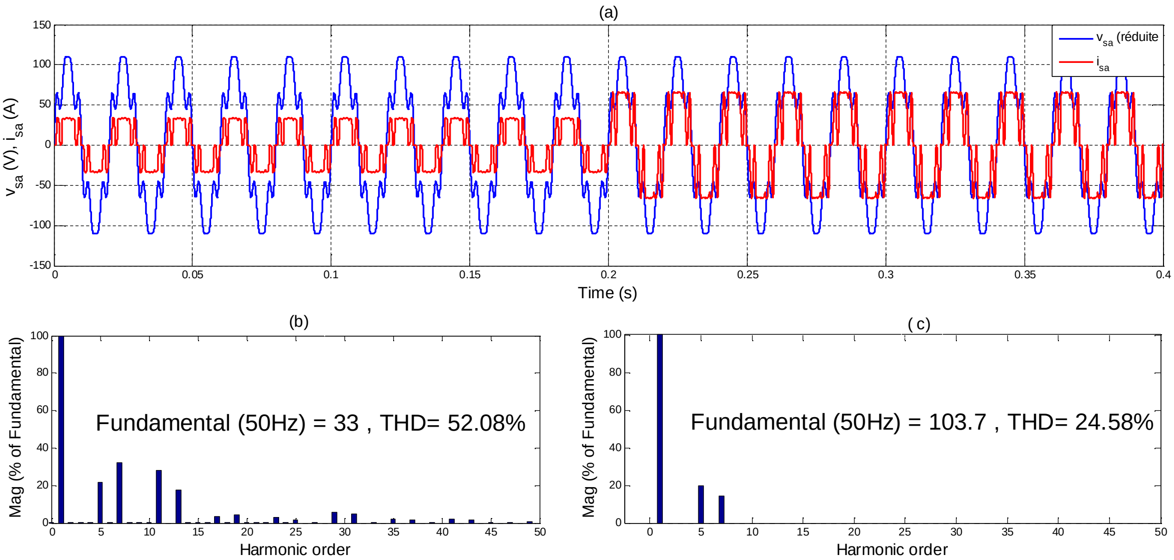

Fig. 8. Simulation results of the perturbed system before compensation. a): Source voltage and source current of a-phase, b): Harmonic spectrum of source current, c): Harmonic spectrum of source voltage

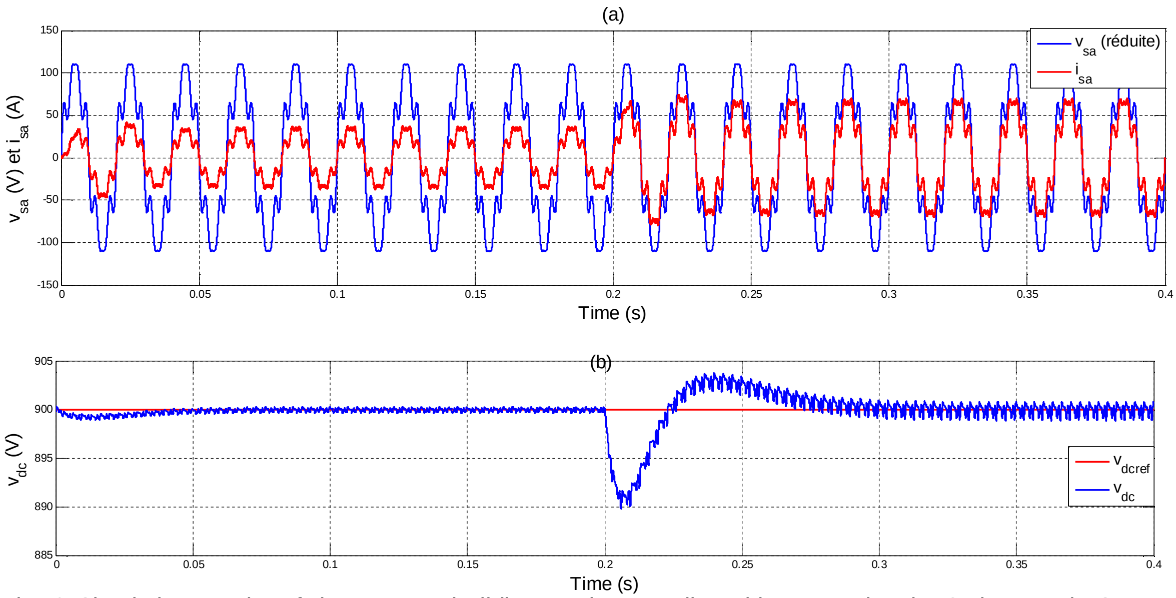

Fig. 9 Simulation results of the proposed sliding mode controller with conventional PQ theory. a): Source voltage and source current of a-phase after compensation, b): DC-link voltage v_{dc}.

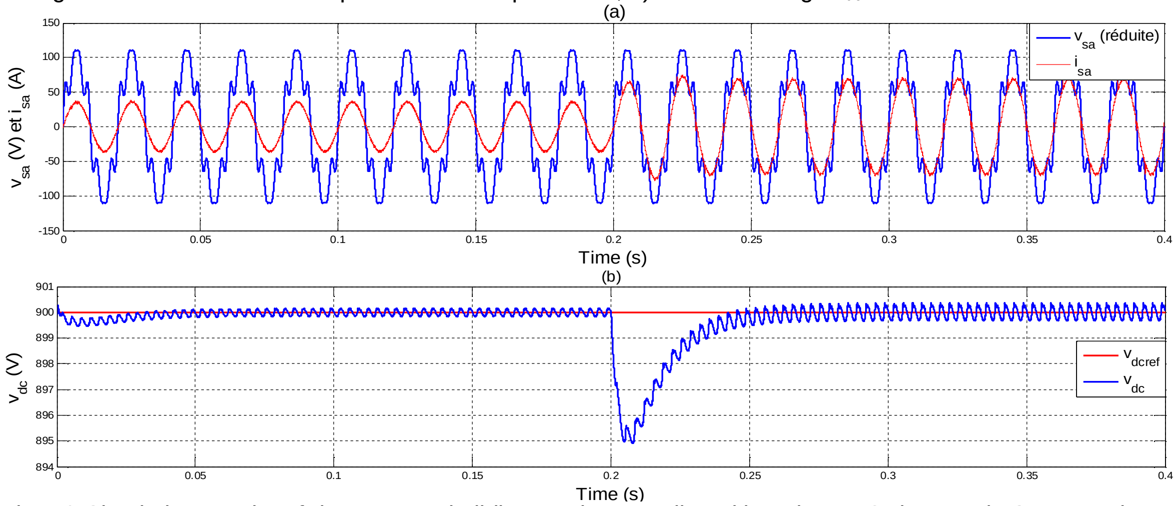

Fig. 10 Simulation results of the proposed sliding mode controller with Robust PQ theory. a): Source voltage and source current of a-phase after compensation, b): DC-link voltage v_{dc}.

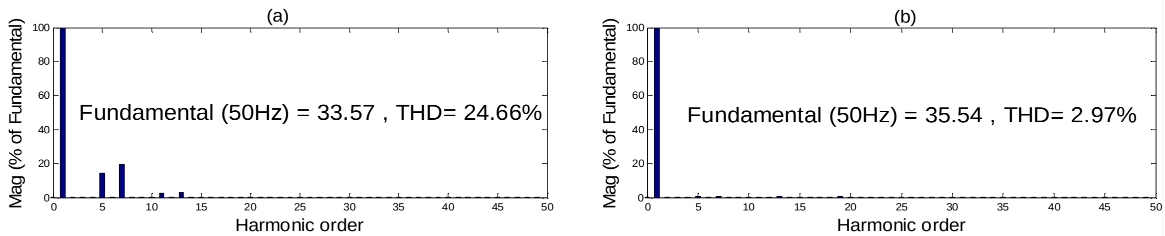

Fig. 11 Harmonic spectrum. a): Harmonic spectrum of source current with conventional PQ theory, b): Harmonic spectrum of source current with robust PQ theory.

The dynamic behavior under a step change of the load at t = 0.2s is presented in Figs. 9.(a) and 10.(a) It can be observed that the grid current become sinusoidal after the control application the case of robust PQ extraction method, in the other hand there is no enhancement with the conventional PQ , however the unity power factor operation is successfully achieved in two cases, even in the transient state.

the harmonic spectrum of AC grid current before and after compensation are illustrated in Fig. 8.(b) and (c), and, in Fig. 11.(a) and (b). It results that the SHAPF decreases the total harmonic distortion (THD) in the grid currents from 52.08% to 24.66% with SMC-PQ which not acceptable, while it is further decreases to 2.97% when SMC-Robust PQ is applied.

The absence of an overshoot in DC voltage response during load change, low rise time and low THD, demonstrates the superiority of the proposed control scheme compared to its counterpart conventional controller as illustrated in Table. 2.

Table1 System parameters

Factor	SMC-PQ	SMC-Robust PQ
THDi (%)	24.66	2.97
Charging of DC link (s)	0.08	0.06
Overshoot	+	-

4. CONCLUSION

In this paper a control design of the SHAPF is carried out including its mathematical model and harmonic extraction methods where we have chosen a conventional PQ and a modified PQ based on MVF. A combined sliding mode space vector modulation controller is derived to regulate injected currents. The control of the inverter is derived from space vector modulator due to its benefits in term of fixed frequency and ease of implementation.

Because it absolutely restored to the balanced set of sinusoidal the source currents under unbalanced source voltage and single-phase loads in the case of SMC-Robust PQ, it has been establish as a successful solution to power quality problems.

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