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Research Article

Design and Analysis of Sliding Mode Controller and Simplified Space Vector Modulation for Three Phase Shunt Active Power Filter

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Abstract: The main aim of this study is to control a multivariable coupled system by choosing sliding mode switching function. A Sliding mode control approach is developed to control a three phase three wire voltage source inverter operating as a shunt active power filter. Hence, no need to divide the system model developed in the synchronous 'dq' reference frame into two separate loops. Furthermore, the proposed control strategy allows a better stability and robustness over a wide range of operation. When sine PWM is used for generation of pulses for the switches, a variable switching nature is exhibited. The pulses for the active filter are fed by a Space Vector Modulation in order to have a constant switching of converter switches. But, the conventional space vector modulation, if implemented practically, needs a complicated algorithm which uses the trigonometric functions such as arctan, Sine and Cosine functions which in turn needs look up tables to store the pre-calculated trigonometric values. In this study, a very simplified algorithm is proposed for generating Space vector modulated pulse for all six switches without the use of look up tables and only by sensing the voltages and currents of the voltage source inverter acting as shunt active filter. The simulation using PSIM and MATLAB software verifies the results very well.

Keywords: Pulse width modulation, shunt active power filter, sliding mode control, space vector modulation

INTRODUCTION

With the widely used single-phase electric devices and increased high power electric appliance, it becomes more and more obvious that the quality of power supply drops and power factor reduces because of nonlinear factors. Since power electronic device and nonlinear load seriously damage the power quality, they have become the main harmonic pollution source of power network. APF could compensate the harmonics generated by the load current through injecting compensation current to the grid, having the advantages of high controllability and fast response. It not only can compensate harmonics, but also can inhibit the flicker and compensate reactive power; therefore, it is an effective approach to suppress the harmonic pollution.

In recent years, the research and design of APF have made great progress and a large number of successful APF products have been put into market. Along with the rapid development of precision, the speed and reliability in hardware equipment, high performance algorithm and real time control can be realized. The models of APF (The Matlab Mathworks, 2000), have been established using various methods and the behavior of reference signal tracking has been improved using advanced control approaches. Rahmani *et al*. (2010) presented a nonlinear control technique with experimental design and single phase shunt active filter was designed by Komucugil and Kukrer (2006) for three-phase shunt APF. Singh *et al*. (2007) and Elangovan *et al*. (2005, 2006) designed a simple fuzzy logic-based robust APF and design of sliding mode controller and intelligent controller to minimize the harmonics for wide range of variation of load current under stochastic conditions respectively. Bhende *et al*. (2006) proposed TS-fuzzy controlled APF for load compensation. Montero *et al*. (2007) compared some control strategies for shunt APFs in three-phase four-wire systems. Matas *et al*. (2008) and Ramos-Carranza *et al*. (2008), succeeded in linearizing the mathematical model of APF with feedback linearization method. Hua *et al*. (2009) and Komucugil and Kukrer (2006) used Lyapunov function to design some new control strategies for single-phase shunt APFs. Chang and Shee (2004) proposed novel reference compensation current strategy for shunt APF control. Pereira *et al*. (2011) derived new strategies with adaptive filters in APFs. Marconi *et al*. (2007) proposed robust nonlinear control of shunt active filters for harmonic current compensation.

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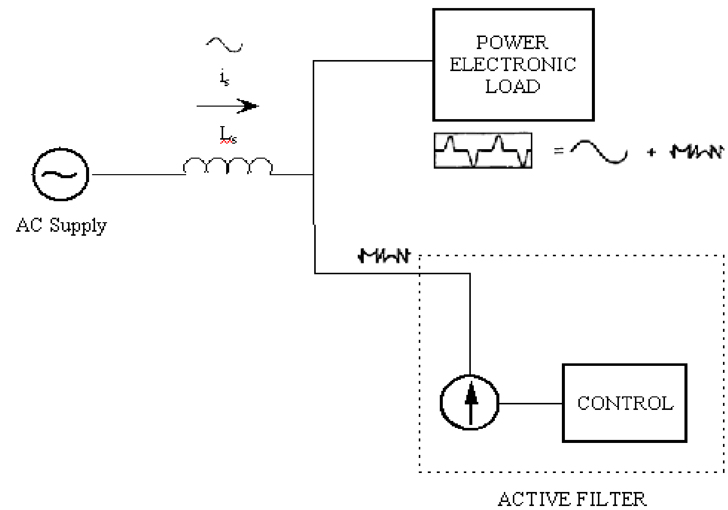

Fig. 1: Generalized shunt active power filter scheme

The concept of using active power filters in order to compensate harmonic currents Jou *et al*. (2005) and reactive power of the locally connected nonlinear loads has been so far investigated and shown to be a viable solution for power quality improvement (Akagi, 1994; Singh *et al*., 1999). Furthermore, the time-varying topology of an active filter makes it suitable to be controlled by a variable structure approach such as the sliding mode one (Sabanovic-Behlilovic *et al*., 1993). In addition, the robustness characteristic and the simplicity of the implementation make the sliding mode control particularly attractive (Utkin and Li, 1992) and Robust Adaptive control was presented by Ioannou and Sun (1995), Ribeiro *et al*. (2012) and Valdez *et al*. (2009) and Model reference adaptive shunt active filter was presented by Shyu *et al*. (2008).

In this study the active filter's internal dynamics are used to obtain the desired closed loop dynamics and to select the switching states. The sliding mode switching functions are chosen in such a way that multivariable coupled system is controlled as a whole with no need of divide it into separated loops (DeCarlo *et al*., 1988). Further, the proposed control law has a discontinuous component forcing the system's trajectory to the sliding surface and a continuous component namely the equivalent control which is valid on the sliding surface. The active filter performance is tested when compensating for nonlinear load current harmonics and unbalances (Mendalek and Al-Haddad, 2000).

This study also proposes a new simplified algorithm for the solution of the space vector PWM (Ma *et al*., 2004; Zhang and Xu, 2001) to the least degree by avoiding finding the solutions of the trigonometric functions and is easy to implement practically. In this study, a very simplified algorithm is proposed for generating Space vector modulated pulse for all six switches without the use of look tables and by only by sensing the voltages and currents of the voltage source inverter acting as shunt active filter

METHODOLOGY

System modelling: The considered shunt active filter is a 3-phase 3-wire inverter (Fig. 1). When this type of converter is controlled into the 'dq' reference-frame rotating at the supply fundamental frequency, the positive-sequence components at this frequency become constant and the effect of the interaction between the three phases is avoided at the switching state decision level.

The reference transformation of the model to the synchronous frame is given by:

$$\begin{bmatrix} \frac{di_d}{dt} \\ \frac{di_q}{dt} \\ \frac{dv_{dc}}{dt} \end{bmatrix} = \begin{bmatrix} -\frac{R_c}{L_c} & \omega & 0 \\ -\omega & -\frac{R_c}{L_c} & 0 \\ 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} i_d \\ i_q \\ v_{dc} \end{bmatrix} + \begin{bmatrix} -\frac{v_{dc}}{L_c} & 0 \\ 0 & -\frac{v_{dc}}{L_c} \\ \frac{i_d}{C} & \frac{i_q}{C} \end{bmatrix} \begin{bmatrix} u_1 \\ u_2 \end{bmatrix} + \begin{bmatrix} \frac{v_d}{L_c} \\ 0 \\ 0 \end{bmatrix} \tag{1}$$

The model (1) is a multivariable nonlinear, namely bilinear system. It exhibits multiplication terms between the state variables {id, iq, vdc} and the inputs {u1, u2}. However the model is time invariant during a given switching state. It can be written into the following general form:

$$X = AX + B(X)u + G \tag{2}$$

Sliding mode controller:

General: The model's state variables {id, iq, v_{dc}} are the d-axis and the q-axis AC currents and the DC voltage respectively. Each of the two currents has to track its harmonic reference and the DC voltage has to be regulated at a fixed set point.

Therefore, in order to apply the proposed control law, the load currents are measured and their harmonic components are extracted and transformed to the 'dq' frame to be used as the current harmonic references. The convergence rate of the state variables can be fixed arbitrarily by suitable selection of the sliding mode parameters. The sliding mode switching functions are chosen to be:

$$\sigma = \begin{bmatrix} \sigma_d \\ \sigma_q \end{bmatrix} = \begin{bmatrix} k_1(X_1 - X_1^*) + k_2(X_3 - X_3^*) \\ k_1(X_2 - X_2^*) + k_2(X_3 - X_3^*) \end{bmatrix} \tag{3}$$

where X^* is the reference state variable vector.

These sliding mode switching functions represent the references to be tracked by the system's state variables.

The proposed control law is (Singh *et al*., 1999):

$$u = u_{eq} + u_N$$

$$\text{with } u = \begin{bmatrix} u_1 \\ u_{21} \end{bmatrix}, u_{eq} = \begin{bmatrix} u_{eq-d} \\ u_{eq-q} \end{bmatrix} \text{ and } u_N \begin{bmatrix} u_{N-d} \\ u_{N-q} \end{bmatrix} \tag{4}$$

In this control law the equivalent control part ueq is valid only on the sliding mode surface and the second part uN assures the existence of the sliding mode. The latter is given by the following:

$$u_{N-d} = \begin{Bmatrix} sgn(\sigma_d) & \sigma_d \neq 0 \\ 0 & \sigma_d = 0 \end{Bmatrix}$$

and,

$$u_{N-q} = \begin{Bmatrix} sgn(\sigma_q) & \sigma_q \neq 0 \\ 0 & \sigma_q = 0 \end{Bmatrix} \tag{5}$$

where sgn (X) is the sign function.

In sliding mode the trajectory of the state variables follows the switching surface dσ/dt = 0.

Sliding mode stability: Given the Lyapnov's function: $U = {}^1/_2\, \sigma^T \sigma$ in order to obtain a sufficient condition for the stability in the sliding mode operation, we must have: $U = {}^1/_2\, \sigma^T \sigma < 0$ when $\sigma \neq 0$.

In fact, this condition represents the sufficient condition for the existence of the sliding mode and assures the trajectory attraction toward the switching surface. Thus, the expression of dσ/dt is:

$$\frac{d\sigma}{dt} = K\left(AX + B(X)\left(u_{eq} + sgn(\sigma)\right) + G\right) - K\dot{X}^* = KB(X).sgn(\sigma) \tag{6}$$

Thus, the stability condition can be written as:

$$\sigma^T \dot{\sigma} = \left(-k_1 \frac{V_{dc}}{L_c} + k_2 \frac{i_d}{C}\right) sgn(\sigma_d)\sigma_d + k_2 \frac{i_q}{C} sgn(\sigma_q)\sigma_d + k_3 \frac{i_d}{C} sgn(\sigma_q)\sigma_q + \left(-k_1 \frac{V_{dc}}{L_c} + k_3 \frac{i_q}{C}\right) sgn(\sigma_q)\sigma_q < 0 \tag{7}$$

Which may be transformed into the following inequality:

$$-k_1 X_3 + \frac{L_c v_{dc} sgn(\sigma_d) + i_q sgn(\sigma_q)}{C\ \sigma_d sgn(\sigma_d) + \sigma_q sgn(\sigma_q)} (k_2\sigma_d + k_3\sigma_q) < 0 \tag{8}$$

The appropriate values of k1, k2 and k3 are selected such that the condition (8) holds true.

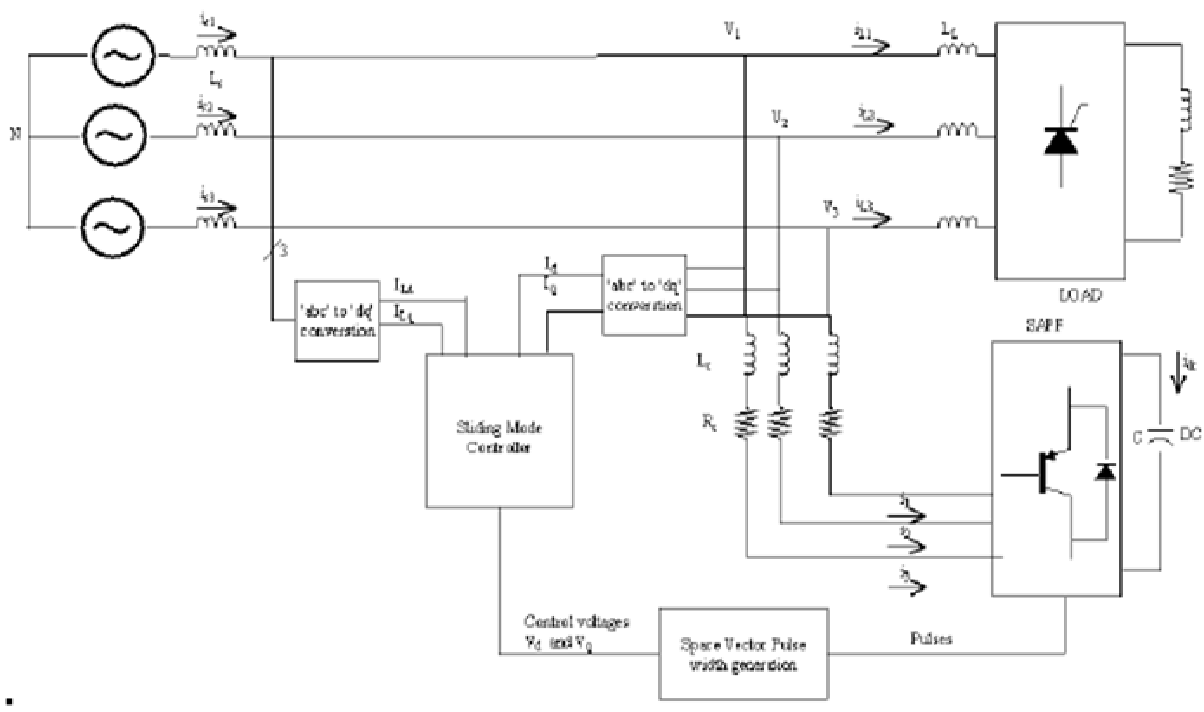

Fig. 2: Shunt active power filter with sliding mode control

Existence of the equivalent control: The existence of the equivalent control of the sliding mode is obtained by setting σ = 0, which gives:

$$u_{eq} = -\left(K \quad BX\right)^{-1} K \left(AX + G - \dot{X}^*\right) \tag{9}$$

The coordinates of the equivalent control are thus obtained as:

$$u_{eq-d} = \frac{-k_1 \frac{R_c}{L_c} i_d + k_1 \omega i_q + k_1 \frac{v_d}{L_c} - k_1 \dot{i}_d^*}{-k_1 \frac{v_{dc}}{L_c} + k_2 \frac{i_d}{C}} - \frac{k_2 \frac{i_q}{C}\left(\frac{R_c}{L_c} i_q + \omega i_d + \dot{i}_q^*\right)}{\frac{v_{dc}}{L_c}\left(-k_1 \frac{v_{dc}}{L_c} i_q + k_2 \frac{i_d}{C}\right)}$$

$$u_{eq-q} = \frac{L_c}{v_{dc}}\left(\frac{R_c}{L_c} i_q + \omega i_d + \dot{i}_q^*\right) \tag{10}$$

The implementation of the sliding mode control strategy is simple. The closed loop scheme is illustrated in Fig. 2.

SIMPLIFIED ALGORITHM OF SPACE VECTOR PWM

The two key problems with the algorithm of space vector PWM are:

- To determine the sector that reference vector located
- Solutions of T_1, T_2, T_0

Sector selection: By conducting research on V_a, V_b and V_c as well as the characteristics of line voltages V_{ab}, V_{bc} and V_{ca}, which are determined by three phase voltages. For the first sector:

$$0 < \theta < \pi/30 < \tan^{-1}\frac{\mathrm{Im}(V_r)}{\mathrm{Re}(V_r)} < \pi/3 \tag{11}$$

From the above the solution can be obtained as:

$$\min\left(|V_{AB}|, |V_{BC}|, |V_{CA}|\right) = -V_{CA} \tag{12}$$

$$\min(V_{AN}, V_{BM}, V_{CN}) = V_{CN} \tag{13}$$

So, if Vr falls into other sectors, further research verifies similar conclusions, which are arranged and collected in Table 1.

Solutions of T_1, T_2 and T_0: Conventionaly, the solutions T_1, T_2 and T_0 are:

Table 1: Solutions of T_1, T_2 and T_0

Sectors	$\min\left(\|V_{AB}\|, \|V_{BC}\|, \|V_{CA}\|\right)$
1	$-V_{CA}$
2	V_{BC}
3	$-V_{AB}$
4	V_{CA}
5	$-V_{BC}$
6	V_{AB}

Table 2: Solutions of T_1, T_2 and T_0

Sectors	T_1	T_2	$T_0 = T_1 + T_2$
1	$\frac{V_{ab}T}{V_d}$	$\frac{V_{bc}T}{V_d}$	$-\frac{V_{ca}T}{V_d}$
2	$-\frac{V_{ca}T}{V_d}$	$-\frac{V_{ab}T}{V_d}$	$\frac{V_{bc}T}{V_d}$
3	$\frac{V_{bc}T}{V_d}$	$\frac{V_{ca}T}{V_d}$	$-\frac{V_{ab}T}{V_d}$
4	$-\frac{V_{ab}T}{V_d}$	$-\frac{V_{bc}T}{V_d}$	$\frac{V_{ca}T}{V_d}$
5	$\frac{V_{ca}T}{V_d}$	$\frac{V_{ab}T}{V_d}$	$-\frac{V_{bc}T}{V_d}$
6	$-\frac{V_{bc}T}{V_d}$	$-\frac{V_{ca}T}{V_d}$	$\frac{V_{ab}T}{V_d}$

$$T_1 = \frac{\sqrt{3}|V_r| T \sin(\pi/3 - \theta)}{V_d} \tag{14}$$

$$T_2 = \frac{\sqrt{3}|V_r| T \sin(\theta)}{V_d} \tag{15}$$

$$T_0 = T - T_1 - T_2 \tag{16}$$

For avoiding the trigonometric functions, the new solutions can be written as.
For the first sector:

$$T_1 = \frac{V_{AB}T}{V_d} \quad T_1 + T_2 = -\frac{V_{CA}T}{V_d}$$
$$T_0 = T - T_1 - T_2 = T + \frac{V_{CA}T}{V_d} \tag{17}$$

If Vr fall into other sectors, we may through analyses, get similar results, which are arranged and collected into Table 2. As can be seen from this table, if the sector that Vr falls in is known, we can find the solutions of T_1, T_2 and T_0 conveniently.

RESULTS AND DISCUSSION

In order to validate the accuracy of the proposed controller, the system was simulated using the “Power System Blockset” in MATLAB/SIMULINK environment (Hua *et al*., 2009). The parameters used are shown in Table 3.

Table 3: Simulation parameters

System parameter	Value
Supply Voltage (Vs)	230V (rms) /P
Frequency (f)	50 Hz
Inductance (Lc)	4.5 mH
Resistance (Rc)	0.1 ohms
DC Capacitance (C)	1000 μF
K_1, k_2 and k_3	0.8, 0.4 and 0.1

The power circuit of the system is simulated using PSIM software. The control circuit of the system is simulated using MATLAB/SIMULINK. For the selection of sectors and the instantaneous calculation of T_1, T_2, T_0 MATLAB coding was used.

We used the simcoupler module of PSIM software for the data sharing between MATLAB and PSIM

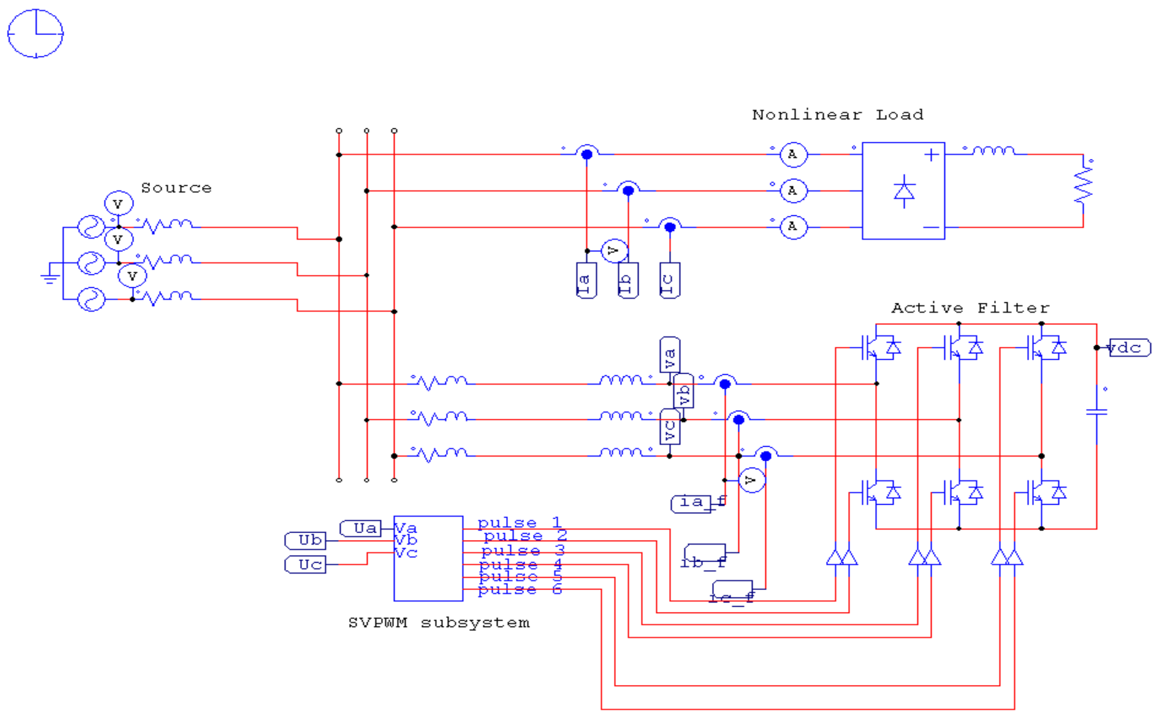

Fig. 3: Simulation of the overall system

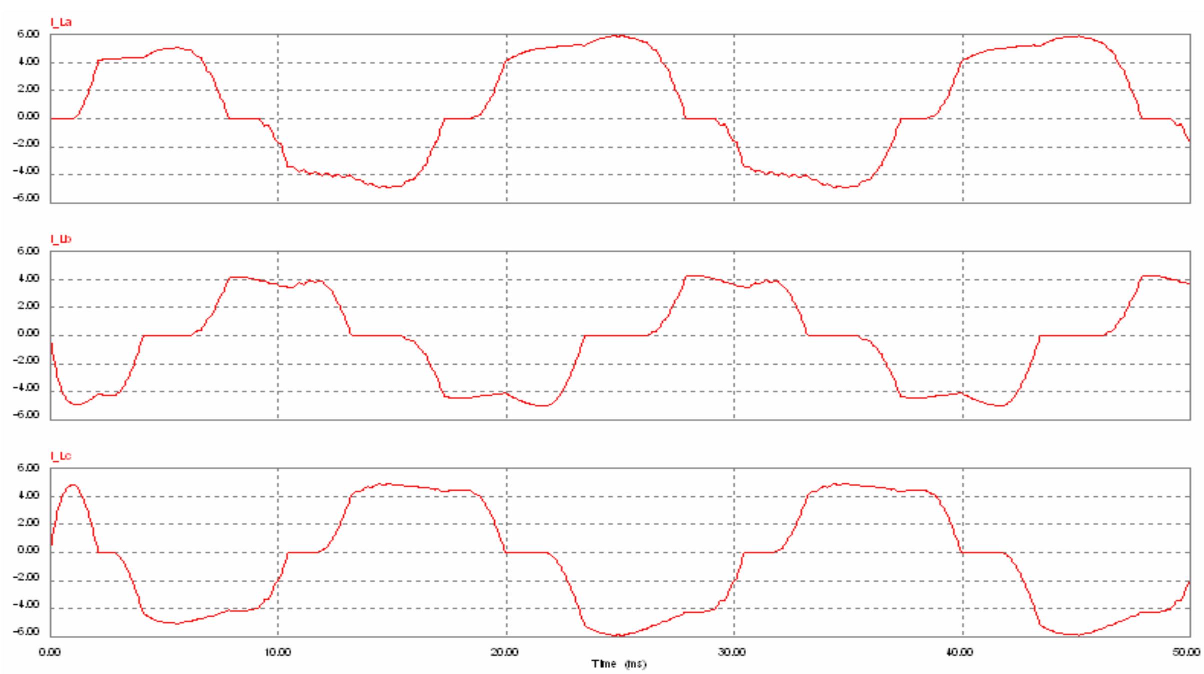

Fig. 4: Non linear load current

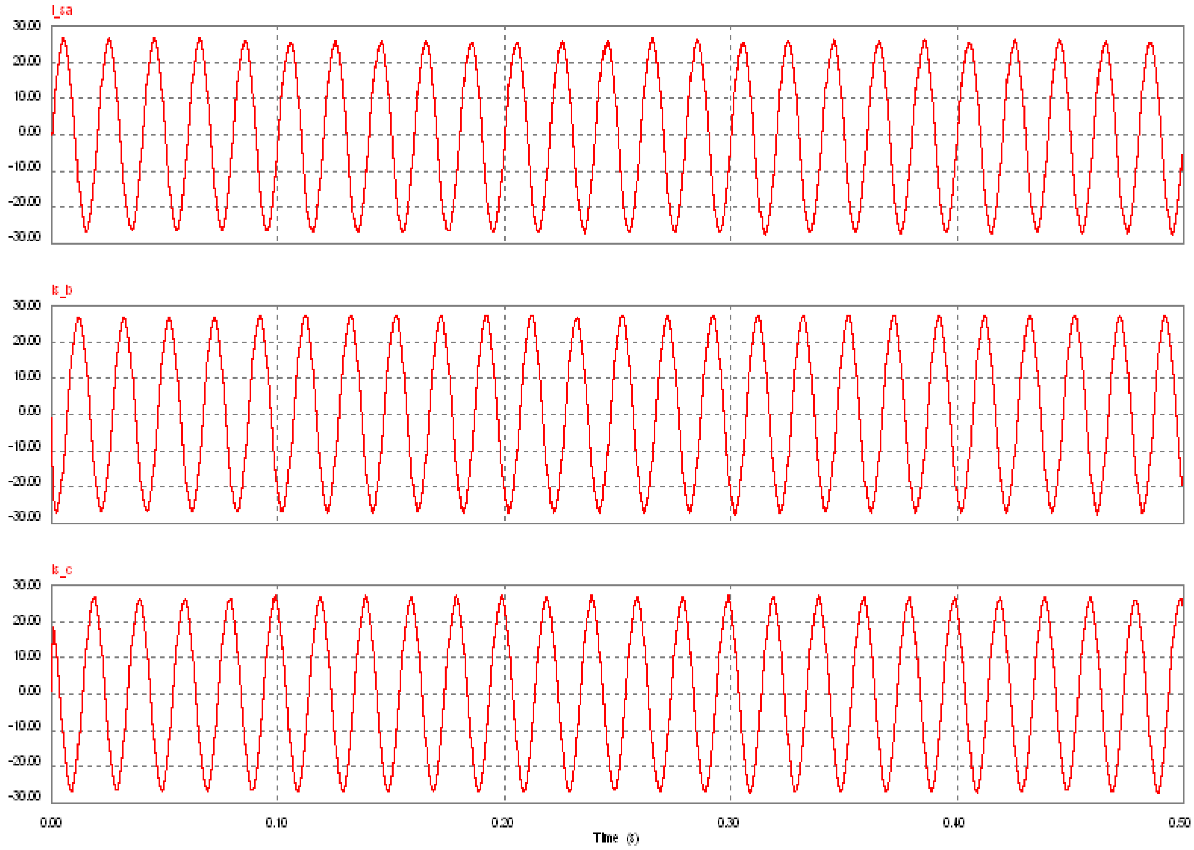

Fig. 5: Supply current after compensation

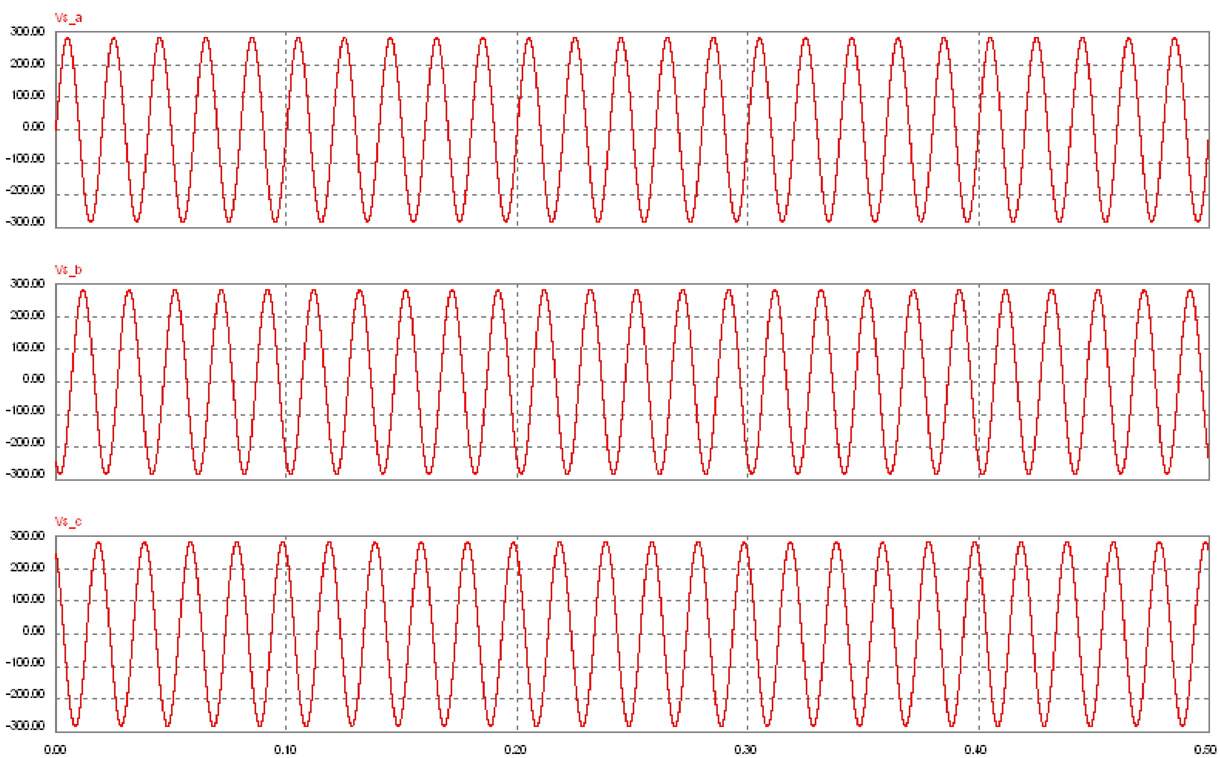

Fig. 6: Supply voltage

software. The power circuit simulated is shown in the Fig. 3.

The goal of the simulation is to examine the capability of the controller to fulfill the following three different aspects:

- Current harmonic compensation
- Dynamic response performance
- Load unbalance compensation

Current harmonic compensation: Figure 4 shows the non-linear load current waveforms in steady state operation. The load consists of a three-phase thyristor bridge feeding an inductive load. The ac supply currents after compensation are illustrated in Fig. 5. The phase-1 current harmonic spectrums are depicted in Fig. 6. It results that the active filter decreases the Total Harmonic Distortion (THD) in the supply currents from 26.6% THD of load currents to 3.1%.

Dynamic response performance: In order to examine the dynamic behavior of the system a 100% step variation of the non-linear load is performed at time t = 110 msec. The load and the supply currents into phases 1 and 2 as well as the active filter dc voltage are depicted in Fig. 6.

CONCLUSION

It is found that the shunt active power filter controlled with sliding mode-strategy is effective to eliminate the current harmonics, to produce the reactive power and to compensate for unbalances of nonlinear loads. Both the current errors elimination and the dc voltage regulation are solved together in-order to obtain the switching functions of the active filter. Simulation results presented support to theoretical predictions.

This study will also give a better solution for the implementation of space vector modulator in a very simplified manner if it is implemented using DSP or FPGA without the use of look up tables. So, this study paves the way for a System on chip solution for any complicated control of motor control applications.

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