Design and Implementation of Sliding Mode and PI Controllers based Control for Three Phase Shunt Active Power Filter

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Abstract

This paper presents a simulation and experimental comparative study of Sliding Mode Controller (SMC) and Proportional Integral (PI) regulator based the control of the DC bus voltage of three phase shunt Active Power Filter (APF). The capacitor that feeds the active filter plays the role of a voltage source. This tension must be kept constant, so as not to degrade the filter performances, and not to exceed the voltage of semiconductors. The main cause of the variation of this voltage is the change in the pollutant load, which creates an active power exchange with the network (if the inverter provides power active, then the average voltage across the capacitor will decrease and if the inverter consumes power active, then the average voltage across the capacitor will increase). The algorithm used to identify the reference currents is based on the Self Tuning Filter (STF). This study was verified experimentally, using a hardware prototype based on dSPACE-1104.

Keywords — Active Power Filter (APF), Sliding Mode Controller (SMC), Self Tuning Filter (STF), Proportional Integral (PI) Controller.

1. Introduction

Industrial and domestic equipments actually use a large variety of power electronic circuits such as switch mode power converters, adjustable speed drives, rectifiers and dimmers. These ones lead to significant energy savings and productivity benefits. But unfortunately, they also present non-linear impedance to the supply network and therefore generate non-sinusoidal currents. The outcome of these wide-band current harmonics includes substantially higher losses for the transformers and the power lines, possible over voltages and overheating destroying equipments and disturbances of communication equipments and precision instruments [1]. So, it is necessary to develop techniques...
to reduce all the harmonics as it is recommended in the IEEE 519-1992. The first approach consists in the design of LC filters. Traditionally, passive LC filters have been used to eliminate line current harmonics, and to improve the load power factor [1]. However, in many practical applications, this passive second order filters present many disadvantages such as tuning problems, series and parallel resonance. They can also lead to resonance phenomena. In recent years, shunt active power filters, based on current controlled PWM converters have been widely investigated. The APF can solve the problems of harmonics and reactive power simultaneously. The theories and applications of active power filters have become more popular and have attracted great attention since two decades ago. Since its introduction some twenty years ago, the APF presents a good solution for disturbance treatment, particularly for harmonic currents and/or voltages. The APF allows the compensation of current harmonics and unbalance, together with the power factor correction, and can be a much better solution than the conventional approach [2], [4].

The identification approach is based on the Phase Locked Loop (PLL), which is not sensitive to the disturbances, specifically to the harmonic and unbalanced voltage [3], [10]. Moreover, the Self Tuning Filter (STF) is proposed for extracting harmonic currents instead of classical harmonics extraction based on High Pass or Low Pass Filters [5]. The sliding mode strategy provides a systematic approach to the problem of maintaining stability and performance in the presence of modeling uncertainty. The most advantage of a sliding mode control is its insensitivity to parametric uncertainty and external disturbances. Therefore, the sliding mode control is suitable for the closed loop control of power converters. Many researchers have paid attention to the application of sliding mode control to power converters with improving the dynamic behavior of the system, endowing it with robustness against changes in the load, uncertain system parameters and simple implementation [6], [7], [8]. These hybrid controllers try to ensure the asymptotical stability and to reduce the chattering by combining sliding mode control with other techniques, such as adaptive control techniques, fuzzy control techniques and ANN-Based Predictive [9], [10], [11]. The regulation of this voltage is necessary to keep its value constant, and to limit the fluctuations of this voltage. The control of the DC bus voltage of the APF is associated in several studies with different regulators [8], [9], [10], [11], [12].

In this paper, first the circuit configuration of the APF system is presented. Second, the control strategy is developed according to the circuit configuration. After this, the SMC and PI design are presented taking in consideration the stability conditions. Finally, detailed simulation and experimental results of the developed APF system are given and discussed to demonstrate their dynamic performances and their ability for harmonic elimination and reactive power compensation.

2. System Configuration

Fig. 1 shows the fundamental building block of the APF. The last one is composed of a standard 3-phase IGBT based VSI bridge with an input AC inductors (L_F, R_F) and a DC bus capacitor C to provide a self-supporting DC bus. The three phase AC supply system with the line impedance L_s, R_s is feeding a three-phase diode bridge rectifier with R_l, L_l load. This nonlinear load generates harmonic currents in the supply system. The current drawn from the power system at the coupling point of the APF will result in sinusoidal waveform. The source current is the result of summing the load current i_L and the compensating current i_F.

The control strategy can be divided in three parts: The first part is the harmonic isolator (reference current generation). It consists in generating the harmonic current references using the Self Tuning Filter (STF). This Filter is proposed for extracting harmonic currents instead of classical harmonics extraction based on High Pass or Low Pass Filters [5].
3. Control of the APF

3.1. Identification of reference currents

The quality of the compensation of current harmonics depends heavily on the performance of the identification method chosen. Indeed, a control system, even very effective, cannot alone make a good filter if the harmonic currents are poorly identified. For this reason, many identification methods have been developed in the literature. There are many control algorithms available for the generation of reference source currents for the control of proposed active power filter in the literature, synchronous reference frame theory[13], [14], instantaneous reactive power theory (p–q theory) [7], [15], power balance theory. A block diagram of the controlling algorithm is shown in Fig. 2. The feedback signals are sensed from the load currents, AC source voltages and DC bus voltages of APF. The three phase currents $i_{La}$, $i_{Lb}$ and $i_{Lc}$ are transformed from three phase (a-b-c) reference frame to two phase’s α-β stationary reference frame currents $i_α$ and $i_β$ using:

$$
\begin{bmatrix}
    i_α \\
    i_β
\end{bmatrix} = \begin{bmatrix}
    2 & 1 & -1/2 \\
    \sqrt{3} & 0 & -\sqrt{3}/2
\end{bmatrix} \begin{bmatrix}
    i_{La} \\
    i_{Lb} \\
    i_{Lc}
\end{bmatrix}
$$

(1)

The instantaneous current can be written as the sum of a fundamental component and an alternative component:

$$
\begin{cases}
  i_α = \hat{i}_α + \tilde{i}_α \\
  i_β = \hat{i}_β + \tilde{i}_β
\end{cases}
$$

(2)

Then, the STF extracts the fundamental components at the pulsation $ω_c$ directly from the currents in the α-β axis. Then, the α-β harmonic components of the load currents are computed by subtracting the STF input signals from the corresponding outputs (see Fig.3). The resulting signals are the AC components, $i_α$ and $i_β$, which correspond to the harmonic components of the load currents $i_{La}$, $i_{Lb}$ and $i_{Lc}$ in the stationary reference frame. Using a PLL (Phase
Locked Loop), we can generate $\cos(\theta)$ and $\sin(\theta)$ from the phase voltage source $V_{sa}$, $V_{sb}$ and $V_{sc}$. The currents expression $i_\alpha$ and $i_\beta$ in d-q reference frame are given by:

$$
\begin{bmatrix}
\tilde{i}_d \\
\tilde{i}_q
\end{bmatrix}
= \begin{bmatrix}
\sin(\theta) & -\cos(\theta) \\
\cos(\theta) & \sin(\theta)
\end{bmatrix}
\begin{bmatrix}
\tilde{i}_\alpha \\
\tilde{i}_\beta
\end{bmatrix}
$$

(3)

The reference currents in the (a-b-c) frame are given by:

$$
\begin{bmatrix}
i_{*a}^F \\
i_{*b}^F \\
i_{*c}^F
\end{bmatrix}
= \sqrt{\frac{2}{3}}
\begin{bmatrix}
1 & 0 & \frac{\sqrt{3}}{2} \\
-1 & \frac{\sqrt{3}}{2} & 0 \\
\frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} & 0
\end{bmatrix}
\begin{bmatrix}
i_{*a}^F \\
i_{*\beta}^F
\end{bmatrix}
$$

(4)

The STF in Fig. 3 is used in the harmonic isolator instead of classical extraction filters. Hong-sock Song in [5] had presented that the integration in the synchronous reference frame is defined by:

$$V_{xy}(t) = e^{j\omega t} \int e^{-j\omega t} U_{xy}(t) dt
$$

(5)

The equation (5) can be expressed as follows: following transfer function [5], [12]:

$$
\tilde{i}_a(s) = \frac{K}{s}[i_a(s) - \tilde{i}_a(s)] - \frac{\omega}{s} \tilde{i}_\beta(s)
$$

(6)

$$
\tilde{i}_\beta(s) = \frac{K}{s}[i_\beta(s) - \tilde{i}_\beta(s)] + \frac{\omega}{s} \tilde{i}_a(s)
$$

(7)
3.2. Sliding Mode controller of DC voltage

The sliding mode control has been widely applied to power converters [10], due to its operation characteristics such as fastness, robustness, and stability under large load variations. A simple form of the control action using sliding mode theory is a relay function which is given by equation (8),

$$s(x) = k \cdot \text{sign}(s(x))$$  \hspace{1cm} (8)

The Lyapunov function must be decreases to zero; for this purpose, it is sufficient to assure that its derivative is negative. In order to reduce the chattering phenomenon due to the discontinuous nature of the controller, a smooth function is defined in some neighborhood of the sliding surface with a threshold. If a representative point of the state trajectory moves within this interval, a smooth function replaces the discontinuous part of the control action. Thus, the controller becomes,

$$u_n = \begin{cases} 
\frac{k_c}{\varepsilon} \cdot s(x) & \text{if } |s(x)| < \varepsilon \neq 0 \\
 k_c \cdot \text{sign}(s(x)) & \text{if } |s(x)| > \varepsilon 
\end{cases}$$  \hspace{1cm} (9)

Where, $k_c$ takes the admissible value. In order to regulate the DC voltage $V_{dc}$ and to compensate the losses using an SMC, the block diagram of the regulation is given by Fig. 4. According to Fig.4, the sliding surface $\sigma_c$ is used to synthesis a command current $I^*$. In this case $I^*$ is given by,

$$I^* = k_c \cdot \text{sign}(\sigma_c)$$  \hspace{1cm} (10)

Fig. 4: Bloc diagram for voltage regulation
3.3. PI Controller design

The transfer function for PI controller is defined as:

\[ H_{pf}(s) = K_p + \frac{K_i}{s} \]  \hspace{1cm} (11)

The proportional gain is derived using \( K_P = 2.\xi.\omega_n.C \) that determines the dynamic response of the DC-side voltage control. Similarly, the integral gain is derived using \( K_I = C\omega_n^2 \) that determines it’s settling time \([2],[10]\). The PI controller for the DC-link voltage sets the amplitude of the active current of the APF inverter to regulate the DC-link voltage based on its reference value covering the inverter losses. Subtracting the measured load current, the reference value of the APF current is obtained. Hence, \( K_P = 2.\xi.\omega_n.C \) and \( K_I = C\omega_n^2 \), for \( \xi = 0.707 \) and \( C = 1100 \times 10^{-6} \text{F} \), \( K_P \) and \( K_I \) can be determined.

4. Simulation and experimental Results

To simulate the SMC or PI controlled shunt active power filter, a model in Matlab\Simulink and SimPowerSystems Blockset is developed.

The same experimental test bench parameters are used for simulation. The performances of SMC of the DC bus voltage of three phase shunt active power filter are compared to conventional PI regulator by extensive simulation and experimentation for various operating conditions and parameters variation at permanent and transit response. The same experimental test bench parameters are used for simulation: \( V_m = 120 \text{V} \), \( R_S = 0.42 \Omega \), \( L_S = 2.3 \text{mH} \), \( L_C = 1 \text{mH} \), \( L_f = 3 \text{mH} \), \( R_I = 45 \Omega \), \( L_I = 1.3 \text{mH} \), \( V^{*}_{dc} = 420 \text{V} \), \( C = 1100 \mu\text{F} \), \( \Delta i \) (hysteresis band) = 0.2 A, \( K_C = 1.5 \).

First simulation is done on fixed load, we see that after the connection of the APF, the mains current has a sinusoidal form (see Fig. 5). In permanent response (see Fig. 6), it is clear that the DC-voltage is regulated well around the reference \( V^{*}_{dc} = 420 \text{V} \), the source current has a sinusoidal form and in phase with supply voltage (it is confirmed for the two controllers), which minimizes the reactive power consumed by the inverter, allowing a high power factor operation and with low THD Total Harmonic Distortion (the \( \text{THD}_{\text{SMC}} = 3.53\% \) and the \( \text{THD}_{\text{PF}} = 3.82\% \)) in current.
Secondly, in order to prove the dynamical response of the controllers at a transient condition, the DC side resistance is changed from RL to RL/2. It can be seen from simulation (Fig. 7 and 8), and experimental results (Fig. 9 and Fig. 10), that the voltage controlled by the SMC joined quickly his reference compared to the DC voltage regulated by the PI.

Finally, to confirm the effectiveness of the control of DC voltage using SMC and PI controllers, a double change of the reference is shown 450-300 and 450V. It can be noted that after the transient response, the DC voltage regulated by the SMC follows its reference, there is no overshoot and the settling time is very small (see Fig. 11. and 12.). However the results in transient response obtained by the PI controller, show oscillations around voltage reference.
6. Conclusion

Two different control strategies for a three-phase shunt active power filter employing a digital signal processor DSP were presented in this paper. The first is based on sliding mode control SMC and the second uses a single proportional-integral controller PI. These controllers are used in order to regulate the DC voltage of the three phase shunt active power filter and improving the dynamical performances. Several tests have been performed in order to prove the efficiency of the type of the control. The results obtained by simulations and Experimental, show that the SMC controller offers better performances than the PI.

References