Real Time Control of an Active Power Filter under Distorted Voltage Condition

Safa Ahmed*, Gouichiche Madjid*, Meslem Youcef*, Tedjini Hamza*
*Laboratoire de génie électrique et de Plasma LGEP, Tiaret

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ABSTRACT

This paper, presents three phase shunt active filter under distorted voltage condition, the active power filter control is based on the use of self-tuning filter (STF) for reference current generation and on space vector PWM for generation of pulses. The dc capacitor voltage is controlled by a classical PI controller. The diode rectifier feed RL load is taken as a nonlinear load. The self-tuning filter allows extracting directly the voltage and current fundamental components in the axis without phase locked loop (PLL) under distorted voltage condition. The experiment analysis is made based on working under distorted voltage condition, and the total harmonic distortion of source current after compensation .Self tuning filter based extraction technique is good under distorted voltage conditions. The total harmonic distortion (THD) of source current is fully reduced. The effectiveness of the method is theoretically studied and verified by experimentation.

Corresponding Author:

Safa Ahmed
Laboratoire de génie électrique et de Plasma LGEP, Tiaret
Email: safa.ahmed.ed@gmail.com

1. INTRODUCTION

Recent wide spread of power electronic equipment has caused an increase of the harmonic disturbances in the power systems. The nonlinear loads draw harmonic and reactive power components of current from ac mains. Current harmonics generated by nonlinear loads such as adjustable speed drives, static power supplies and UPS. The harmonics causes problems in power systems and in consumer products such as equipment overheating, capacitor blowing, motor vibration, excessive neutral currents and low power factor. Conventionally, passive LC filters and capacitors have been used to eliminate line current harmonics and to compensate reactive power by increasing the power factor. But these filters have the disadvantages of large size, resonance and fixed compensation behavior so this conventional solution becomes ineffective.

An effective solution to these problems is to use active power filters .These equipment use power electronics to inject suitable anti-phase harmonics in a manner that the utility sees an effective linear load [1].

In this paper, we use a modified version of the p–q theory to compute the reference currant for the APF, this method use the STF (Self Tuning Filter) to extract the fundamental component of the source voltage and the harmonic component of the load current, A SVM (Space vector Modulation) based current controller is implemented to inject the compensating current to the power system so that the APF allows the actual inverter current to follow the reference current.

An active power filter consists of four essential parts namely, (i) the signal conditioning circuit; (ii) the reference current generation circuit, (iii) the control circuit, and (iv) the power converter.

The signal conditioning circuit acquires the essential voltage and current signals to provide accurate system information. The reference current generation circuit generates the required harmonic currents to be amplified and injected into the lines, at the point where the load is connected.

The performances of an active filter mainly depend on the reference current generation strategy. Several papers studied and compared the performances of different reference current generation strategies under balanced, sinusoidal, unbalanced or distorted alternating current (AC) voltages conditions [2–4]. In all of them, authors demonstrated that under balanced and sinusoidal AC voltages conditions, the strategies such as the so-called p–q theory and Synchronous Reference Frame Theory (SRF) provide similar performances. Differences arise when one works under distorted and unbalanced AC voltages [5].

In real conditions, the mains voltages are distorted, which decreases the filter performances [6]. In this case, the p–q theory performances are poor, from the harmonics point of view, and the best results are obtained with the SRF. However, the SRF theory requires a phase locked loop (PLL) which increases the complexity of the control system: an additional card is usually used and the controller implementation is more complex. In this paper, we theoretically and experimentally studied a new reference current generation suitable for shunt active power filter control under distorted voltage conditions by using self-tuning filter (STF) for the reference current generation and a modified version of the classical p–q theory.

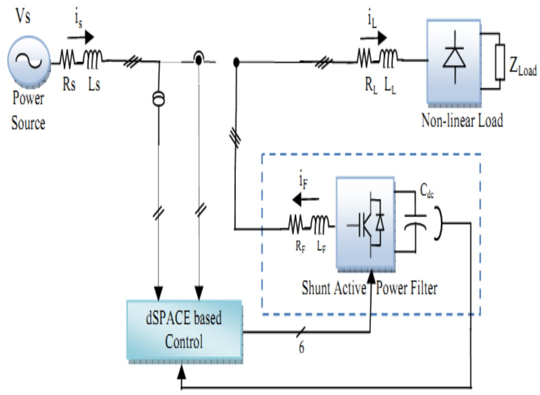

Figure 1. Active Power Filter

2. Control strategy

2.1. General control principle

The self-tuning filter is the most important part of this advanced control which allows making insensible the PLL to the disturbances and filtering correctly the currents in α-ß axis. According to Figure 3, the voltage V_{dc}, the load currents I_{La} and i_{Lb}, and the source voltages v_{sa} and v_{sb} of the three-phase three wire system are acquired and converted into α-ß coordinates. The current i_{Lc} is computed by $i_{Lc} =- (i_{La} + i_{Lb})$ and the voltage v_{sc} is calculated by $v_{sc} =- (v_{sa} + v_{sb})$. Then, we apply a modified version of the p–q theory for generating the current references i^*_{fa}, i^*_{fb} and i^*_{fc} .The generation of switching pulses by modulated hysteresis current controller

2.2. Principle of Self-tuning filter

Hong-sock Song studied the integration in the synchronous reference frame [7]. He demonstrated that:

$$V_{xy}(t) = e^{j\omega t}\int e^{-j\omega t}U_{xy}(t)dt \tag{1}$$

where U_{xy} and V_{xy} are the instantaneous signals, respectively before and after integration in the synchronous reference frame. The previous equation can be expressed by the following transfer function after Laplace transformation.

$$H(s) = \frac{V_{xy}(s)}{U_{xy}(s)} = \frac{s + j\omega}{s^2 + \omega^2} \tag{2}$$

In [8] authors had introduced a constant K in the transfer function H(s), to obtain a STF with a cut-off frequency ω_c so the previous transfer function H(s) becomes:

$$H(s)=\frac{V_{xy}(s)}{U_{xy}(s)}=K\frac{(s+K)+j\omega_c}{(s+K)^2+\omega_c^{\ 2}} \tag{3}$$

By introducing the parameter K in H(s), the transfer function magnitude is limited and more particularly equal to one for $\omega=\omega_c$. Moreover, the phase delay is equal to zero for the cut-off frequency ω_c. By replacing the input signals U_{xy}(S) by $x_{\alpha\beta}(s)$ and the output signals V_{xy}(S) by $\hat{x}_{\alpha\beta}(s)$ the following expressions can be obtained.

$$\hat{x}_\alpha(s)=\frac{K(s+K)}{(s+K)^2+\omega_c^{\ 2}}x_\alpha(s)-\frac{K\omega_c}{(s+K)^2+\omega_c^{\ 2}}x_\beta(s) \tag{4}$$

$$\hat{x}_\beta(s)=\frac{K(s+K)}{(s+K)^2+\omega_c^{\ 2}}x_\beta(s)+\frac{K\omega_c}{(s+K)^2+\omega_c^{\ 2}}x_\alpha(s) \tag{5}$$

Where $x_{\alpha\beta}(s)$ and $\hat{x}_{\alpha\beta}(s)$ can both be a current or a voltage signal, respectively before and after filtering. Thus, by using a STF, the fundamental component can be extracted from distorted electrical signals voltage or current without any phase delay and amplitude changing [8].

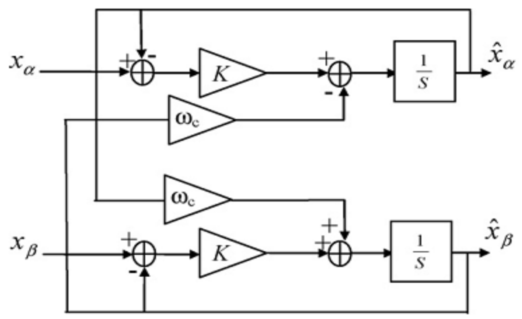

Figure 2. Self-tuning filter tuned to frequency w_c.

2.3. Reference current generation:

The currents in the axis can be respectively decomposed into DC and AC components

$$i_\alpha=\hat{i}_\alpha+\tilde{i}_\alpha \tag{6}$$

$$i_\beta=\hat{i}_\beta+\tilde{i}_\beta \tag{7}$$

The STF extracts the fundamental components at the pulsation ω_c directly from the currents in the axis. After that, the harmonic components of the load currents are computed by subtracting the STF input signals from the corresponding outputs (see Figure 2). The resulting signals are the AC

$$\begin{bmatrix}V_\alpha\\V_\beta\end{bmatrix}=\sqrt{\frac{2}{3}}\begin{bmatrix}1 & -\frac{1}{2} & -\frac{1}{2}\\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2}\end{bmatrix}\cdot\begin{bmatrix}V_{sa}\\V_{sb}\\V_{sc}\end{bmatrix} \tag{8}$$

The self-tuning filter suppresses the harmonic component of the distorted main voltage finally it leads to improve the performance. After computation of the fundamental component $\hat{v}_{\alpha\beta}$ and the harmonic currents $\tilde{i}_{\alpha\beta}$, the p and q powers are calculated as follows:

$$p = i_\alpha \hat{v}_\alpha + i_\beta \hat{v}_\beta \quad (9)$$

$$q = i_\beta \hat{v}_\alpha - i_\alpha \hat{v}_\beta \quad (10)$$

Where $p = \hat{p} + \tilde{p}$, $q = \hat{q} + \tilde{q}$

With $\hat{p}$, $\hat{q}$ fundamental components $\tilde{p}$, $\tilde{q}$: alternative components the power components $\tilde{p}$ and $\tilde{q}$ related to the same α-β voltages and currents can be written as follows:

$$\begin{bmatrix} \tilde{p} \\ \tilde{q} \end{bmatrix} = \begin{bmatrix} \hat{V}_\alpha & \hat{V}_\beta \\ -\hat{V}_\beta & \hat{V}_\alpha \end{bmatrix} \cdot \begin{bmatrix} \tilde{i}_\alpha \\ \tilde{i}_\beta \end{bmatrix} \quad (11)$$

After adding the active power required for regulating DC bus voltage, p_c, to the alternative component of the instantaneous real power, $\tilde{p}$ (see Figure 3), the current references in the α-β reference frame, i^*_α , i^*_β are calculated by:

$$i^*_\alpha = \frac{\hat{v}_\alpha}{\hat{v}_\alpha^{\,2} + \hat{v}_\beta^{\,2}} (\tilde{p} + p_c) - \frac{\hat{v}_\beta}{\hat{v}_\alpha^{\,2} + \hat{v}_\beta^{\,2}} \tilde{q} \quad (12)$$

$$i^*_\beta = \frac{\hat{v}_\beta}{\hat{v}_\alpha^{\,2} + \hat{v}_\beta^{\,2}} (\tilde{p} + p_c) - \frac{\hat{v}_\alpha}{\hat{v}_\alpha^{\,2} + \hat{v}_\beta^{\,2}} \tilde{q} \quad (13)$$

With substitution of (11) into (12) and (13), we obtained:

$$i^*_\alpha = \tilde{i}_a + \frac{\hat{v}_\alpha}{\hat{v}_\alpha^{\,2} + \hat{v}_\beta^{\,2}} p_c \quad (14)$$

$$i^*_\beta = \tilde{i}_\beta + \frac{\hat{v}_\beta}{\hat{v}_\alpha^{\,2} + \hat{v}_\beta^{\,2}} p_c \quad (15)$$

Current references obtained from Eqs. (14) and (15) include two terms, the first term contains the harmonic current components and the second one is a fundamental current component in phase with the supply voltage. Consequently, a small amount of active power is absorbed from or released to the DC capacitor so as to regulate the DC bus voltage. Then, the filter reference currents in the a–b–c coordinates are defined by

$$\begin{bmatrix} i^*_{fa} \\ i^*_{fb} \\ i^*_{fc} \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & 0 \\ \frac{1}{2} & \frac{\sqrt{3}}{2} \\ -\frac{1}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} i^*_\alpha \\ i^*_\beta \end{bmatrix} \quad (16)$$

2.4. DC bus voltage control

A DC bus controller is required to regulate the DC bus voltage v_{dc} and to compensate for the active filter losses. The measured DC bus voltage v_{dc} is compared with its reference value v_{dc}^*

The resulting error is applied to a proportional integral (PI) regulator. So, the active filter can build up and regulate the DC capacitor voltage without any external power supply.

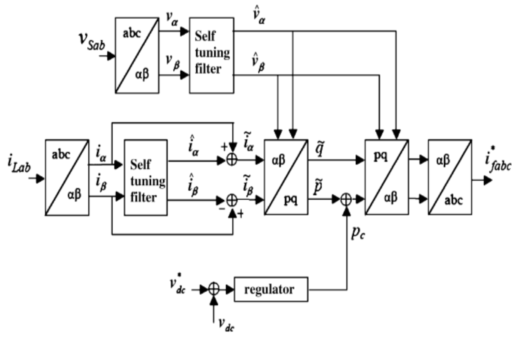

Figure 3. STF's bloc diagram

3. THE THREE-PHASE APF WITH SIMPLIFIED SPACE VECTOR

A typical power stage of a three-phase APF is composed of a voltage-source converter that is connected in parallel with a nonlinear load as shown in Figure 4. The three-phase voltage waveforms v_a, v_b, and v_c of the grid is shown in Figure 5. The three-phase voltage is divided to six regions by across zero-voltage of each voltage waveforms.

3.1. The Selection of Space Vector

The voltage-source converter is operated in CCM mode and the driver signals to the switches in each arm are set to be complementary, i.e. the duty ratios of switches S_{an}, S_{ap} in phase A are d_{an} and $d_{ap}=1-d_{an}$ respectively.

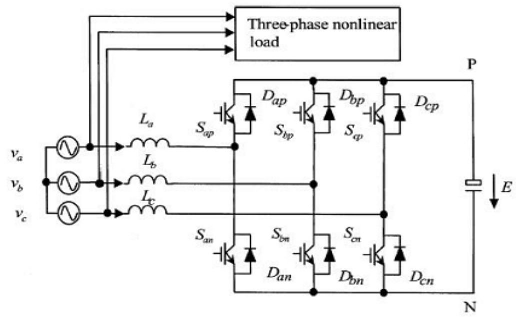

Figure 4. Three-phase two level APF

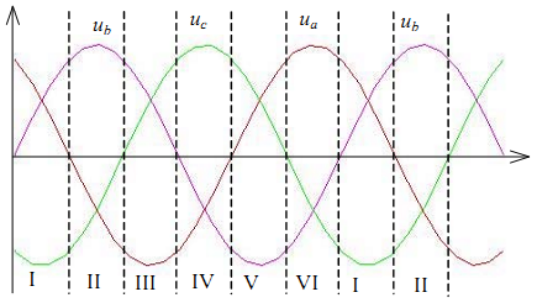

Figure 5. Three-phase voltage waveform with regions

In Figure 4 the average node voltages for node D, E, F referring to the bridge "N" can be write as

$$\begin{cases} u_{DN} = d_{ap}E \\ u_{EN} = d_{bp}E \\ u_{FN} = d_{cp}E \end{cases} \tag{17}$$

Under the state of rectifier and the symmetrical state of three-phase system,

$$u_{NO} = -\frac{1}{3} E(d_{ap} + d_{bp} + d_{cp}) \tag{18}$$

Since the switching frequency is much higher than the line frequency,

$$\begin{cases} L\dfrac{di_{ac}}{dt} = u_a - [d_{ap}E - \dfrac{1}{3}E(d_{ap} + d_{bp} + d_{cp})] \\ L\dfrac{di_{bc}}{dt} = u_b - [d_{bp}E - \dfrac{1}{3}E(d_{ap} + d_{bp} + d_{cp})] \\ L\dfrac{di_{cc}}{dt} = u_c - [d_{cp}E - \dfrac{1}{3}E(d_{ap} + d_{bp} + d_{cp})] \end{cases} \tag{19}$$

V'* is bridge arm midpoint voltage vector,

$$(V - V'^*) = L\frac{\Delta \mathrm{I}_c}{\Delta \mathrm{T}} = L\frac{dI_c}{dt} \tag{20}$$

Where:

$$V = \frac{2}{3}(u_a + u_b\alpha + u_c\alpha^2) \tag{21}$$

$$V'^* = \frac{2}{3}(u'^*_a + u'^*_b\,\alpha + u'^*_c\,\alpha^2) \tag{22}$$

$$\Delta \mathrm{I} = \frac{2}{3}(\Delta \iota_{ac} + \Delta \iota_{bc}\alpha + \Delta \iota_{cc}\alpha^2) \tag{23}$$

$$\mathrm{I} = \frac{2}{3}(\iota_{ac} + \iota_{bc}\alpha + \iota_{cc}\alpha^2) \tag{24}$$

3.2. The Formulas of the Duty Ratio

In region I: T_0, T_4, T_6, and ΔT is on off time of voltage vector: V0, V4, V6 and V respectively.

$$\begin{cases} \Delta \mathrm{T} \cdot u_a'^* = T_0 \cdot 0 + T_4 \cdot \dfrac{2}{3}E + T_6 \cdot \dfrac{1}{3}E \\ \Delta \mathrm{T} \cdot u_b'^* = T_0 \cdot 0 + T_4 \cdot \dfrac{-1}{3}E + T_6 \cdot \dfrac{1}{3}E \end{cases} \tag{25}$$

Thus,

$$\begin{cases} \dfrac{T_4}{\Delta \mathrm{T}} = \dfrac{u_a'^* - u_b'^*}{E} \\ \dfrac{T_6}{\Delta \mathrm{T}} = \dfrac{u_a'^* - 2u_b'^*}{E} \end{cases} \tag{26}$$

The duty ratio d_{an}, d_{bn} d and d_{cn} of S_{an}, S_{bn}, and S_{cn} is flow respectively.

$$\begin{cases} d_{an} = 1 - \dfrac{T_4}{\Delta T} - \dfrac{T_6}{\Delta T} = 1 - \dfrac{2u_a'^* + u_b'^*}{E} \\ d_{bn} = 1 - \dfrac{T_6}{\Delta T} = 1 - \dfrac{u_a'^* + 2u_b'^*}{E} \\ d_{cp} = 0 \end{cases} \quad (27)$$

Under the state of invert and the symmetrical state of three-phase system. In region I:

$$\begin{cases} d_{ap} = \dfrac{T_4}{\Delta T} + \dfrac{T_6}{\Delta T} = \dfrac{2u_a'^* + u_b'^*}{E} \\ d_{bp} = \dfrac{T_6}{\Delta T} = \dfrac{u_a'^* + 2u_b'^*}{E} \\ d_{cn} = 1 \end{cases} \quad (28)$$

In region I, from equation (28), the voltage vectors are accordant and the formulas of duty ratio are complementary.

So, the formulas of duty ratio under the state of rectifier and under the state of invert can be uniform. The voltage vector and uniform duty ratio formulas under the state of rectifier and invert form region I form VI are showed in the table I.

Table 1. Formulas of duty cycle in each region

Region	Voltage Vector	Duty ratio
I	V0 V4 V6	$d_{ap} = (2u_a'^* + u_b'^*)/E$ $d_{bp} = (2u_b'^* + u_a'^*)/E$ $d_{cp} = 0$
II	V7 V6 V2	$d_{ap} = 1 + (2u_a'^* + u_c'^*)/E$ $d_{bp} = 1$ $d_{cp} = 1 + (2u_c'^* + u_a'^*)/E$
III	V0 V2 V3	$d_{ap} = 0$ $d_{bp} = (2u_b'^* + u_c'^*)/E$ $d_{cp} = (2u_c'^* + u_b'^*)/E$
IV	V7 V3 V1	$d_{ap} = 1 + (2u_a'^* + u_b'^*)/E$ $d_{bp} = 1 + (2u_b'^* + u_a'^*)/E$ $d_{cp} = 1$
V	V0 V1 V5	$d_{ap} = (2u_a'^* + u_c'^*)/E$ $d_{bp} = 0$ $d_{cp} = (2u_c'^* + u_a'^*)/E$
VI	V7 V5 V4	$d_{ap} = 1$ $d_{bp} = 1 + (2u_b'^* + u_c'^*)/E$ $d_{cp} = 1 + (2u_c'^* + u_b'^*)/E$

4. EXPERIMENTAL RESULTS

The STF control method is tested on our laboratory prototype of an SAPF. The SAPF consists of six insulated gate bipolar transistor (IGBT)(Semikron *SKM50GB123D 1200V/50A*).The peak load power is 3.5 kW, The IGBTs are controlled by switching pattern produced by the SVM method, with a switching frequency of 20 KHz.

The harmonic are generated by a nonlinear load (RL load connected to three phase rectifier) and the control algorithm is running in real time using the DSPACE 1104. Figure (1).

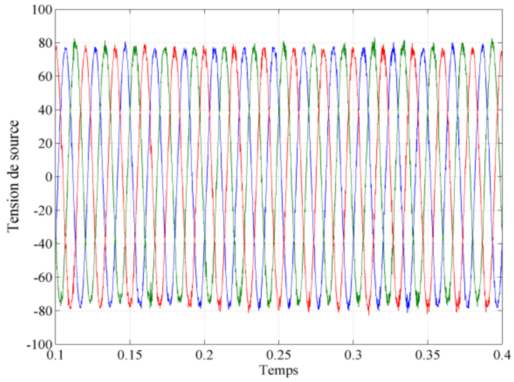

Figure 6. The source voltage

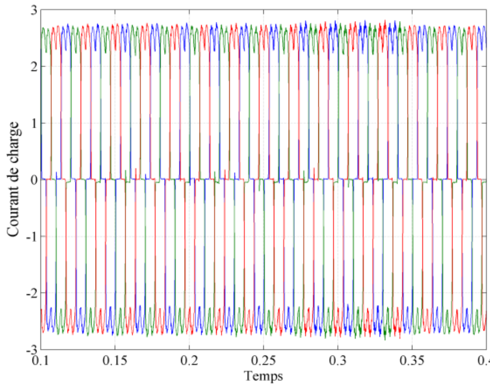

Figure 7. The load current

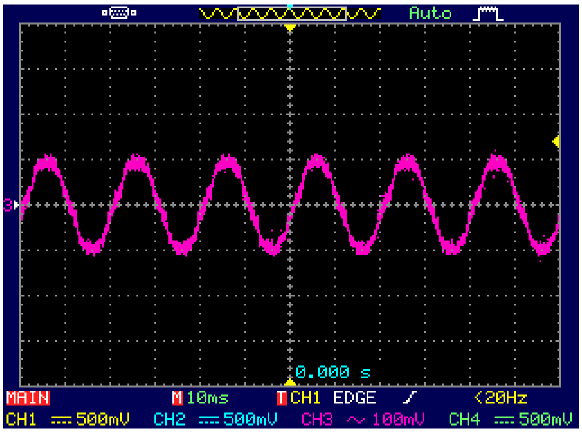

Figure 8. Source current

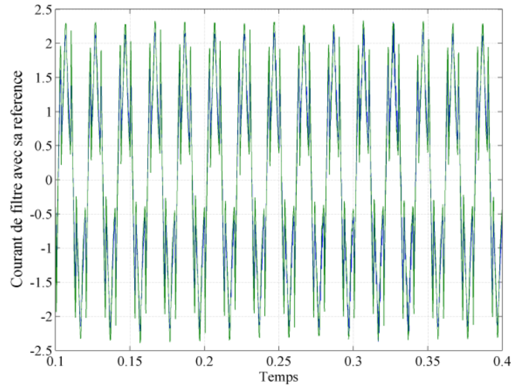

Figure 9. Filter current and its reference

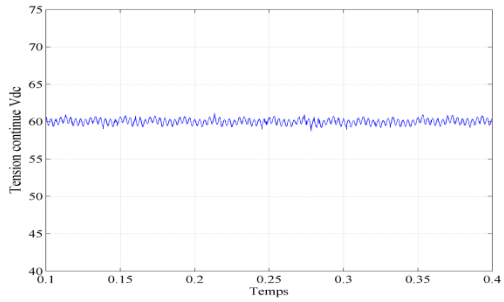

Figure 10. The DC voltage

Figure 6 shows the voltage waveform, it has a THD of 4.35%. Figure 7 shows the waveform of the load current, it has a THD of 28% the current spectrum is presented in Figure11.

Figure 9 presents the inverter current (phase A) and its reference we can see that they are almost identical which prove the efficiency of the SVPWM method.

Figure 8 shows the source waveform; we can see that its form has considerably improved by the SAPF, and the harmonic spectrum in Figure 12 confirm that, where the 5^{th} and 7^{th} have been widely reduced.

Figure 14 shows experimental results for the DC bus controller. The voltage V_{dc} on the DC side of the inverter is stable and regulated around its reference.

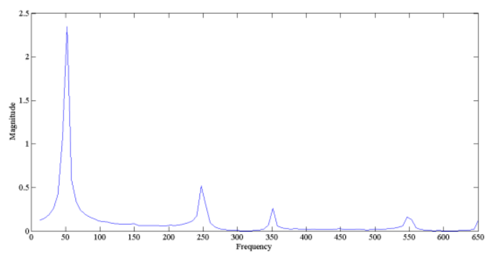

Figure 11. Load current's harmonic spectrum

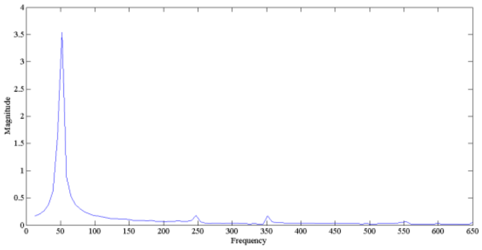

Figure 12. Source current's harmonic spectrum

5. CONCLUSION

A modified pq theory control technique applied to a three-phase Shunt Power Filter is proposed. The appropriate control strategy for removing harmonics caused by non-linear loads is developed. The main advantage of the proposed method is its simplicity (no PLL circuit needed) and its efficiency in non-ideal voltage condition.

The use of SVPWM method allows to the inverter to fellow its reference accurately which increase the performance of the active filter.

The experiment results show the efficiency of the proposed method in terms of harmonic reduction as shown in Figure12, the THD obtained by the new control technique has been drastically reduced.

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