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ACTIVE POWER COMPENSATOR OF THE CURRENT HARMONICS BASED ON THE INSTANTANEOUS POWER THEORY

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Abstract: The quality of the electrical current becomes a major concern. The proliferation of the power electronic converters, which are used extensively to control electrical apparatus in industrial and commercial applications (dc and ac variable speed motor drives, induction furnaces, power line conditioners, and industrial power supplies), is at the origin of the AC current distribution network pollution and the reactive power demand. These power electronic converters typically draw non-sinusoidal currents from the utility, causing interference with adjacent sensitive loads and limit the utilization of the available electrical supply. The quality of the electrical current thus becomes a significant concern for the distributors of energy and their customers. Recent progress as regards technology of the power electronics brings a capacity of compensation and correction of the harmonic distortion generated by the nonlinear loads. In this paper a parallel active filter prototype capable of reducing the total harmonic distortion in the supply for most current source or adjustable speed drive type loads is presented. A 33 kVA active power filter was developed for harmonic and reactive power compensation based on the instantaneous power theory. The active filter configuration requires the measurement of both the load and filter currents. Experimental results from a prototype active power filter confirm the suitability of the proposed approach. The actual 33kVA prototype converter has been built and tested in the SIEI S.p.A. (Italy) laboratory under the Marie Curie Post Doctoral research. The active power compensator is controlled by a high performance DSP platform, resulting in the following active filter features: source current reduction up to the 25^{th} harmonic, 10% THD achievable for current source type loads, efficiency above 97%, does not cause resonance with other loads, operation in the presence of unbalanced loads, reactive power and harmonics compensation capability, load current and source current detection capability.

Keywords: Active Power Filter, instantaneous power theory, harmonics compensation

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1. INTRODUCTION

The quality of the electrical current in the commercial and industrial electric installations is degraded incontestably because of two major reasons: external disturbances such as the cuts, the hollows and the points caused by commutation and the atmospheric phenomena, and internal causes specific to each site, which combines both linear and nonlinear loads.

An inopportune release of the safety devices, harmonic overloads, high levels of the voltages and currents distortion, and the increase in the conductors and the generators temperature as many other factors are contributing to deteriorate the quality and the reliability of an alternative low voltage network.

The aforementioned disturbances are well included/understood, and rise directly from the proliferation of the loads which consume a nonsinusoidal current, called "nonlinear loads". This type of load is used to ensure conversion, the variation and the regulation of the electrical current in the commercial, industrial and residential installations.

The prospect for a fast return to the linear loads conditions is illusory. Recent studies showed that the nonlinear current consumption will increase in a very abrupt way in the next years (Clark, *et al.*, 1994).

In the traditional approach there is the following method in order to suppress harmonics in power systems: the use of shunt passive filters.

However, the remarkable progress made during last years, in the field of the power electronic devices, made possible to design devices for harmonics elimination, named as Active Power Filters. The Harmonics Active Compensators prove to be a valid option for the regulation of the harmonic distortion levels in many applications.

The goal of the compensation is to eliminate the components of power that do not contribute to the net transfer of energy from the source to the load.

Various types of active filters have been proposed in many technical literatures (Clark, *et al.*, 1994; Akagi, 1995; Aburto, *et al.*, 1997; Fujita, H., *et al.*, 1998). Classification of active filters is made from different points of view. Active filters are divided into ac and dc filters. Active dc filters have been designed to compensate for current and/or voltage harmonics on the dc side of thyristor converters for HVDC systems and on the dc link of a PWM rectifier/inverter for traction systems. Emphasis, however, is put on active ac filters because the term "active filters" refers to active ac filters in most cases. From systems' configuration point of view, active power filters can be divided in two classes: series and shunt active filters. The combination of shunt active and passive filters has already been applied to harmonic compensation of large-rated cycloconverters for steel mill drives.

The basic concepts of shunt active power filters were introduced by L. Gyugyi and E. C. Strycula , in 1976 (Gyugyi and Strycula, 1976). The first active power filter prototypes based on instantaneous power theory was reported in (Akagi, H., *et al.*, 1983). Low frequency harmonics (2^{nd} ~ 13^{th} harmonic) should be suppressed because they can excite resonance in the electric network and cause problems such as overvoltage, protection failure, mechanical stress and additional heating.

2. ACTIVE POWER FILTER TOPOLOGY AND RATINGS

Three phase APF's have three and four wires. In this paper the converter has three wires which involve six switches (three lags), one capacitor in the dc side (Raju, *et al.*, 1995; Cardenas, *et al.*, 1998, Kim, *et al.*, 1998; Nishijima, *et al.*, 1998;Yanchao and Fei, 1998) and one line inductance in the ac side.

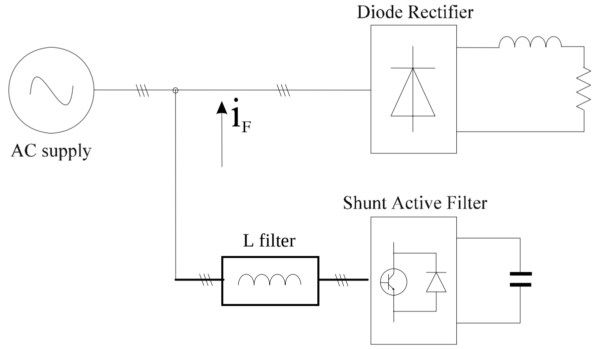

Fig.1. The connection of the shunt active filter

Figure 1 shows a block diagram of the parallel active filter connection. It consists of a dc link inverter and filter section, controller and feedback signals. The filter inductor is used to convert the voltage source inverter output to a current source capable of injecting harmonic currents (i_F) to the load. The configuration exhibited in Figure 1 uses load current feedback. The system is capable of using utility source current feedback wherein the harmonic currents are minimized. The available prototype is rated at 48 rms [A] of harmonic correction current for 400 [V] ac service. The parallel active filter supplies the harmonic current required by the total load, allowing the source to supply only the fundamental component. The main active filter specifications are in Table 1. Power currents are measured with isolated Hall transducers (LEMs), mains-circuit voltages by means of protective impedances according to EN 50178. Both the apparatus incoming current and the distorting load current must be measured by external transducers (Gaiceanu, 2004).

Table 1 Active Filter Specifications (48 rms [A] unit)

Type **AHF**		**22kW**
U_{LN}	Vac	3 x 400 ± 15% or 3 x 460 –10% ÷ 3 x 480 +10%, 48 ÷ 62Hz
$\cos\varphi_{L1}$		≥ 0,95
THD of I_{LN} (ref. to I_{L1} and @ I_{SC} = 100)	%	≤10
Modulation type		Space vector PWM
Default switching (modulation) frequency	kHz	4
Rated power (@ 400/480 Vac, cl. 1)	kVA	30
I_{FN} cl. 1 (@ f_{SW} = default)	A	54
I_{FN} cl. 2 (@ f_{SW} = default)	A	48
Short term overload current	A	200% of I_{FN} cl. 2 for 0,5 sec. over 60 sec cycle time. (Overload time adapts to the heatsink temperature T_H.)
"Higher" switching frequency	kHz	16
Dimensions H x W x D	mm	2000x900x600
T_A (func.)	°C	0 … + 40; +40 … + 50 with derating
Degree of protection		IP20.
Approvals		CE

2.1 EMC rules

In conformity to good electromagnetic compatibility (EMC) practice (Gaiceanu, 2004), power layout design and related control circuits will follow appropriate general rules:

- minimise stray inductances and capacitances;
- avoid parallel run of separate circuit paths;
- run back and forth paths of power supply lines in parallel;
- minimise electromagnetic field emissions avoiding stray flux of magnetic circuits;
- keep signal circuits possibly far from power circuits and use Faraday boxes around signal circuits where needed;
- keep return paths as short as possible, on printed circuit boards trace big ground reference areas,
- use twisted and shielded wire pairs for signal interconnect of remote (30cm) circuits;
- use galvanic isolation (optocouplers, transformers) where safety isolation is needed or common mode noise interference (ground loops) must be rejected;
- use braided bonding bars to interconnect and ground metallic parts (boxes, cabinets, heatsinks, shields so on);
- whenever possible avoid electromagnetic noise emission limiting dV/dt and dI/dt values occurring inside circuits;
- cut locally possible overvoltages (opening of switches, coils, etc.) using voltage transient suppressors like varistors, crowbars, diodes, snubbers and so on.

3. THE STRUCTURE OF THE CONTROL SYSTEM

A technique one very powerful and that it have been very much used is the instantaneous power theory (IPT) or well-known as *pq Theory* (Akagi, H., et al., 1983).

According to it, starting from the phase voltages (e_u, e_v, e_w) and the load currents (i_{La}, i_{Lb}, i_{Lc}) instantaneous values of the three phase system (Peng, et al., 1997), is possible to calculate the real and imaginary (reactive) instantaneous powers of the load, p_L, q_L. For reactive power compensation, it is sufficient the action of the APF. For harmonics compensation it is necessary to separate the instantaneous power in DC and oscillating components, and to supply only the constant real power. The structure of the control system for the active power filter is shown in Fig.2.

The control system consists in the current and the voltage loops. The current control system is performed in the *a*, *b*, *c* phase, fixed reference frame. The generation of the references is performed according to the Akagi method (Akagi, H., *et al.*, 1984). Control logic is essentially based on the calculation of the load active and reactive power and therefore of the consequent phase and module of the current that must be generated in the system from the active filter. The calculation of the current references of the filter is shown in Fig.2. The instantaneous real power, p_L, and the instantaneous reactive power, q_L, flowing into the load side are the inputs of the P-Q Conversion block.

The real power, p_L, and the imaginary one, q_L, are given by:

$$\begin{bmatrix} p_L \\ q_L \end{bmatrix} = \begin{bmatrix} e_\alpha & e_\beta \\ -e_\beta & e_\alpha \end{bmatrix} \begin{bmatrix} i_{L\alpha} \\ i_{L\beta} \end{bmatrix} \quad (1)$$

From previous equation, p_L and q_L are decomposed in two values of power:

$$p_L = \overline{p}_L + \tilde{p}_L \quad (2)$$

$$q_L = \overline{q}_L + \tilde{q}_L \quad (3)$$

where $\overline{p}$ and $\overline{q}$ are the dc load current components (fundamental) and $\tilde{p}$ and $\tilde{q}$ are the ac load current

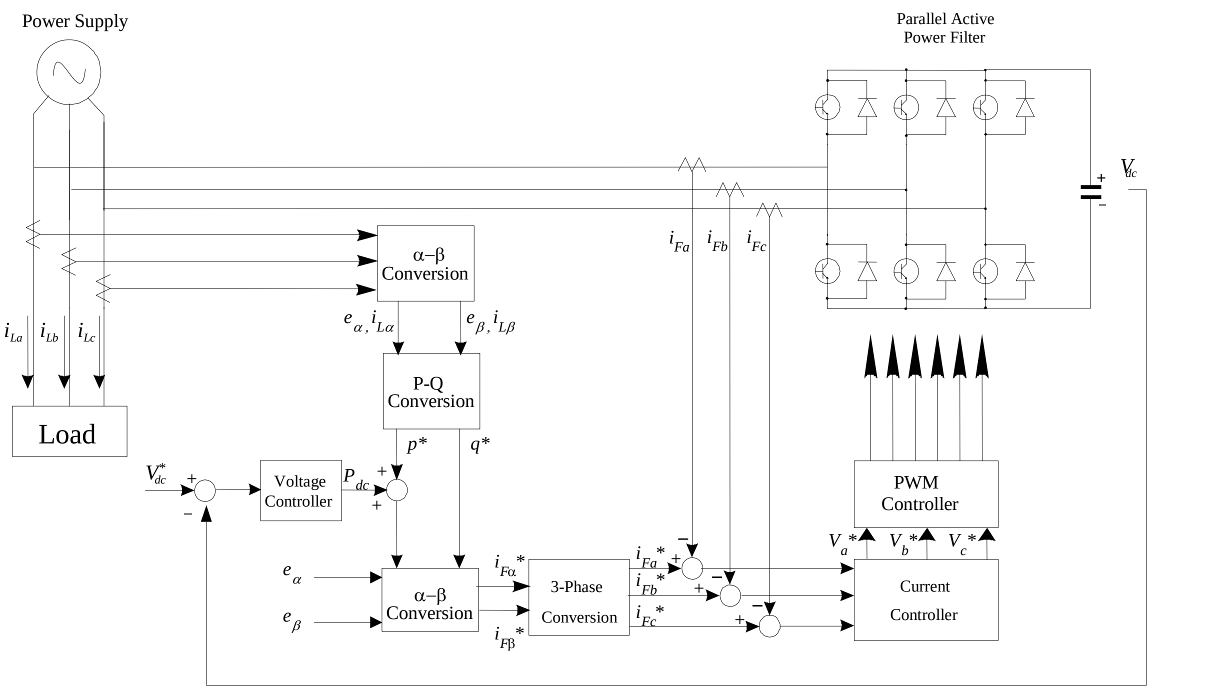

Fig.2. The control system of the parallel filter

components corresponds to the harmonics. In the active filter for the current harmonics compensation, the following power components p^* and q^* are given by the P-Q Conversion circuit, which should be the harmonic components of the p_L and q_L:

$$p^* = \tilde{p}_L \quad , \quad q^* = \tilde{q}_L \tag{4}$$

The circuit of p^* and q^*calculation, represented in figure 3, consists in two high-pass filters with the same cutoff frequency. The design of the high-pass filter has a great effect on the compensation in transient state or in steady state. In order to minimize the influence of the high pass filter's phase responses, high pass filter was obtained by using the low pass (Butterworth) one of the same order and cutoff frequency. The q-axis high pass filter can be eliminated in case of reactive power compensation.

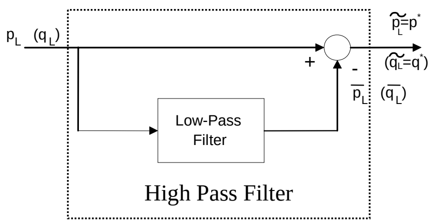

Fig.3. The p* and q* calculation circuit.

The instantaneous real power, P_{dc}, necessary to adjust the capacitor voltage to its references, V^*_{dc}, is added to harmonic component of the load power p*.
The calculation of the current setpoints $i^*_{Fa}, i^*_{Fb}, i^*_{Fc}$, are carried out by means of the following equations:

$$\begin{bmatrix} i^*_{Fa} \\ i^*_{Fb} \\ i^*_{Fc} \end{bmatrix} = \sqrt{2/3} \begin{bmatrix} 1 & 0 \\ -1/2 & \sqrt{3}/2 \\ -1/2 & -\sqrt{3}/2 \end{bmatrix} \cdot \begin{bmatrix} e_\alpha & e_\beta \\ -e_\beta & e_\alpha \end{bmatrix}^{-1} \cdot \begin{bmatrix} p^* + P_{dc} \\ q^* \end{bmatrix} \tag{5}$$

in which P_{dc} is the real power calculated from the voltage loop. A proportional-integral controller performs the voltage regulation.
The current loop control system is implemented in the fixed axes a, b, c reference frame. The used current regulator is a proportional-integral one.

4. EXPERIMENTAL RESULTS

Experimental results from 33kVA active power filter prototype confirm the suitability of the proposed approach. An outline of the system power part and of the parallel filter connection is shown in Fig.1. The diode bridge rectifier is used as an ideal harmonic generator to study the performance of the active filter. The filter is connected in parallel with the load being compensated. Therefore, the configuration is referred as the parallel or shunt filter. This converter uses dc capacitors as the supply and can switch at the high frequency to generate a signal that will cancel the harmonics from the nonlinear load (the diode bridge rectifier). The SKM150GB124D IGBT power module was used.

4.1 Performances

Test plots showing the performances of active power filter 48 rms [A], 400 [V] unit are presented in Fig.5. The harmonic load is a 45 kW diode rectifier feeding a DC motor load and drawing line currents with 57,7% THD (Fig.4).

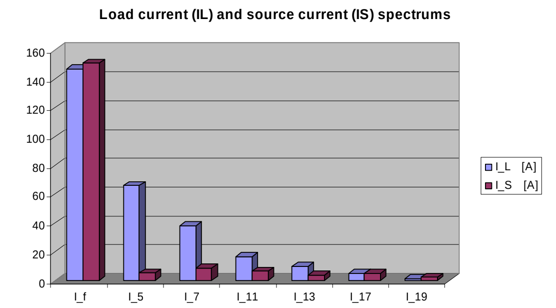

Fig.4: The spectrums of the nonlinear load current (I_L) and of the source current (I_S)

By using active power filter, the Total Harmonic Distortion of the source current is decreasing to 9,1% (Fig.4).

The obtained active power filters' phase current (IF_A) spectrum is shown in Fig.5.

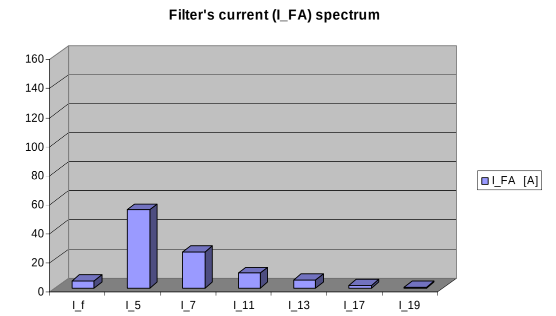

Fig.5 The spectrum of the active power filter phase current (IF_A)

The following waveforms (Fig.5) demonstrate the active filter's ability to clean up the source harmonics, reducing the line currents up to 10% THD (Fig.6).

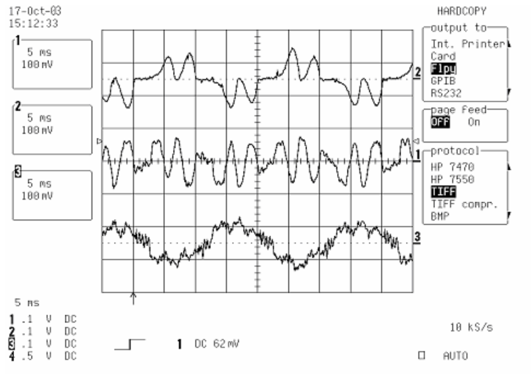

Fig.4: From top to bottom- Source Utility Current (50 A/div, 5msec/div) – without active filter- 57,7% current THD; Active Power Filter's compensating current (50A/div, 5msec); Source utility current (50A/div, 5msec) with active filter operating- 9,7% current THD.

5. CONCLUSIONS

A prototype of the active power current harmonics compensator based on the instantaneous power theory has been performed. The topology and ratings, the electromagnetic compatibility rules, the structure of the control, and the experimental results of the APF were presented. The *pq Theory* needs the use of the Clark transformation. The controller of the APF uses the low pass filter instead of the high ones in order to minimize the influence of the high pass filter's phase responses. The experimental results on the 33 kVA, 400V prototype unit confirm the current harmonics reduction. The active power compensator is controlled by a high performance DSP platform, resulting in the following active filter features: source current reduction up to the 25th harmonic, 10% THD achievable for current source type loads, efficiency above 97%, does not cause resonance with other loads, operation in the presence of unbalanced loads, reactive power compensation capability, load current and source current detection capability. The paper found out a great investment in the researches and technological development of APF's. The development of new switching techniques and of the semiconductors devices will continue enlarging perspectives of applications to the APF's.

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