INDIRECT CONTROL OF A LOW POWER SINGLE-PHASE ACTIVE POWER FILTER

Silviu Epure, Emil Rosu

“Dunarea de Jos” University of Galati, Romania

Abstract: This paper deals with a low power, single phase active filter used to compensate nonlinear loads. The filter uses the indirect control method and it is based on a particular connection between filter, polluting load and grid to avoid time-consuming mathematic operations or signal processing computations and assures good rejection of harmonic currents injected by the nonlinear load into the grid. A scale model was first simulated in Simulink and then physically implemented. The paper presents simulation and experimental results, and highlight problems encountered during experiments.

Keywords: active power filtering, indirect control, PWM rectifier, THD.

1. INTRODUCTION

Low power, single phase nonlinear loads becomes widely used nowadays. In particular, personal computers and notebooks are used and acquired based on the performance criteria. All those devices act as a variable and nonlinear load into the grid. A short research on the schematic of their power supply show that THD and power factor correction aspect is completely forgotten on all “no-name” devices.

More than this, notebook’s, monitor’s and compact fluorescent lamp’s power supply acts the same way: a rectifier bridge followed by a RC load, with variable resistor.

If only a few nonlinear devices would be connected on a low impedance grid, the cumulative effect of loads would be negligible. But the real situation is exactly opposed: a high number of these loads are present in every office building and the grid impedance is not sufficiently low to counteract the nonlinearities. As a result, the voltage on the grid transforms from a sinusoid, on no-load condition, to a trapezoidal shape on normal-to-high loads. It is even possible that fast-acting fuses on the grid to be triggered on the simultaneously start-up of many nonlinear loads.

Correcting this problem inside every nonlinear load is ideal but inapplicable. Solution consists in using external power filters to smooth current absorbed from the grid. Passive filters could efficiently correct the THD and power factor only on the constant-load condition; but, again, this is far from real situation, where a PC could use at one moment 100W and 10 seconds further – 300W.

This short study of the situation reveals that active power filters (APF) are needed to minimize the impact of multiple low-power nonlinear loads on the grid. Akagi (1996), Singh *et al.* (1999), El-Habrouk *et al*. (2000) presents more details about the power quality improvement using active power filters.

Given the facts that these loads are usually the same type, connected together in a point of the grid, and the cause of the distortions is the content of current harmonics of the loads, a single APF can be used to cancel out the current harmonics injected in the grid.

A shunt active power filter using voltage inverter will be connected in parallel with the polluting loads as in

This paper was recommended for publication by Marian Gaiceanu

Fig.1. Filter consist in a power inverter, a capacitor as energy buffer, some voltage or current transducers, and control loops that control the inverter in the proper manner.

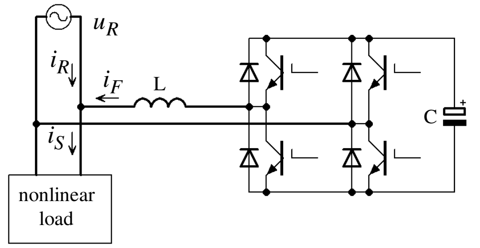

Fig.1. Classical shunt APF structure

Operation of the filter is based on the request that current drawn from the mains

$$(1)\ i_R(t) = i_S(t) - i_F(t)$$

to be sinusoidal and in phase with the grid voltage.

The APF’s current is

$$(2)\ i_F(t) = \tilde{i}_S(t) = i_S(t) - i_S^1(t)$$

where $i_S^1(t)$ is the fundamental and $\tilde{i}_S(t)$ is the “polluting component” - sum of higher order current harmonics and the reactive current.

To determine this polluting component, some complicated procedures need to be used (instantaneous powers method, FFT analysis etc). Some of them are presented by Akagi *et al. (*2007).

Another method, *indirect control*, can be used. It is based on a particular connection between filter, polluting load and grid to avoid difficult mathematic operations, but assures a good rejection of harmonic currents injected by the nonlinear load into the grid. The load and APF are connected together and the resulting system is connected to the grid through an inductor. The structure is presented in Fig.2:

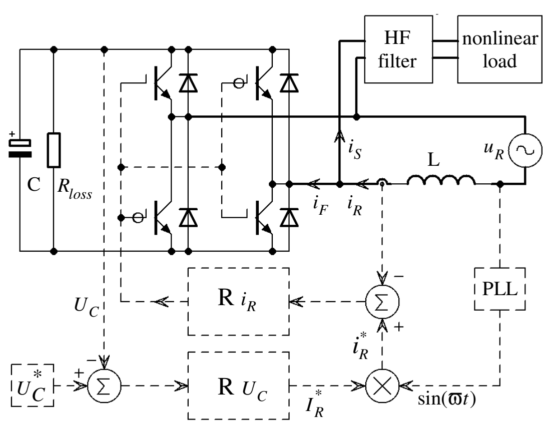

Fig.2. Indirect control APF - control loops

A detailed mathematic analysis of the circuit is presented in Rosu *et al*., (2006).

In short terms, the APF will act such that the sum of APF and load currents is sinusoidal and the equilibrium of active powers is sustained. Operation of the circuit can be described as follows:

- a voltage controller, R_{Uc}, will try to keep constant the energy in the capacitor C; the control the loop is based on assumption that voltage at capacitor is a measure for the stored energy;

- to charge the capacitor and to compensate for losses, the inverter is controlled by the current controller, R_{iR}, with variable duty-cycle PWM signal so that absorbed current from the grid to be sinusoidal;

- nonlinear load connected in parallel with the inverter will change the relation between the absorbed current from the grid and the transferred energy to the capacitor; negative feedback loop will compensate the change by modifying the duty-cycle;

- given the fact that the current loop permits faster current variations between load and capacitor than between load and grid (limited by inductance L), the main current harmonics will be forced to flow between capacitor and nonlinear load;

- because the inverter dissipates negligible active power and the total absorbed current is imposed sinusoidal, results that only active power is drowned from the grid.

2. SIMULATION RESULTS

2.1. The simulation model

A scale model of the circuit was implemented and simulated in Simulink, using SimPowerElectronics toolbox. The two controllers were chosen as simple as possible for easier hardware implementation:

- voltage controller is P type, with $k_{Pu} = 2$;

- concerning the current controller, two situations have been analyzed: first, a hysteresis controller with fixed current error band, and second a PWM controller with fixed frequency.

As seen in Fig.3, the model uses a sinusoidal AC voltage source to power a classical nonlinear load formed by an uncontrolled rectifier coupled with a RC load. A switch is used to alter the resistor’s value at a given time. The active filter needs only two informations: DC-link capacitor voltage, u_C and inductor current, i_R for proper operation.

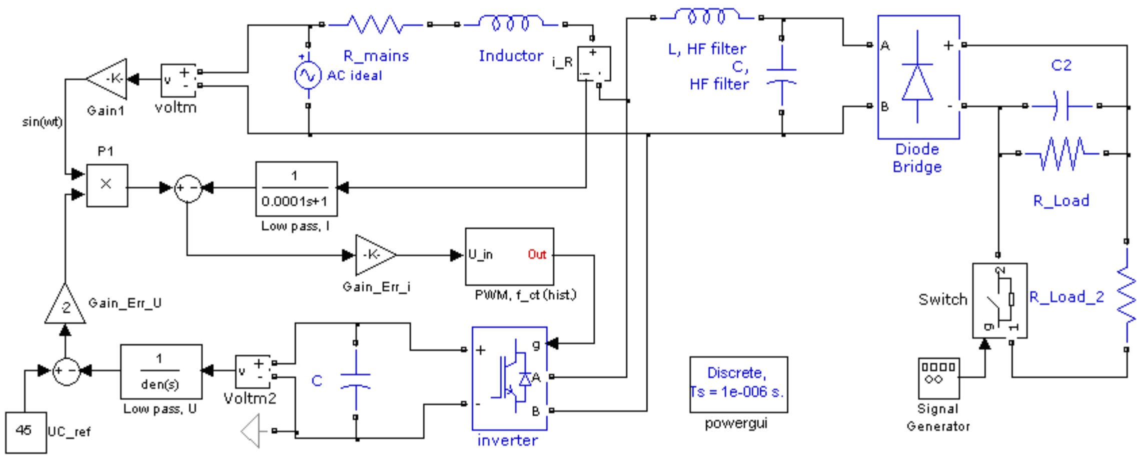

Fig.3. SimPowerSystems model used to simulate the APF operation

Two supplementary passive filters are present in the circuit: - a low-pass, second order filter to cut the 100 Hz component from the U_C signal and - a low-pass first order filter to stop the chopping noise from entering in the current control loop.

All the electronic devices used in the Fig.3. are loaded from SimPowerSystems toolbox in Matlab.

The block *PWM,f_ct(hist.)* detailed in Fig.4 is used to generate the control pulses for the IGBT bridge. The input signal is compared with a triangular signal and the result is used to generate the output pulses.

In order to be used as P controller, the signal generator produce a triangular signal of amplitude 1V, input signal is limited to 0.99V, and the hysteresis blocks have $\pm$ *eps* bandwidth.

In order to be used as hysteresis controller, the amplitude of the signal generator is 0V, and Histerezis1 and Histerezis2 blocks are used to define the controller bandwidth. The two Transport Delay blocks are used to create the dead time needed for proper operation of the IGBT bridge.

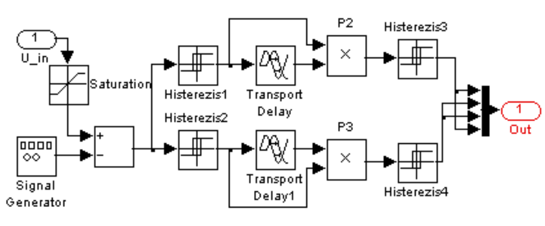

Fig.4. Pulse generator for the IGBT bridge

The values for the circuit components are selected to be close to the ones used on the experimental platform: $u_R = 26\sqrt{2}\sin(\varpi t)$; R_mains = 0,5 Ω ; Inductor = 4 mH ; APF filters capacitor $C = 4700\ \mu F$; LC passive filter for load: $L = 2\ mH$; $C = 330\ nF$; nonlinear load: $C = 1000\ \mu F$, $R = 100\ \Omega$ and the switch will add another $R = 20\ \Omega$.

2.2. Simulation results

Simulation is focused on showing the indirect APF performance, proving that the method can be applied on a low power, single phase active filter.

First, the nonlinear load was analyzed: Fig.5 show the classic waveforms associated with this type of load. The nonlinear aspect of the chosen load is obvious. Fig. 6 presents the harmonics content of the nonlinear current from Fig.5b.

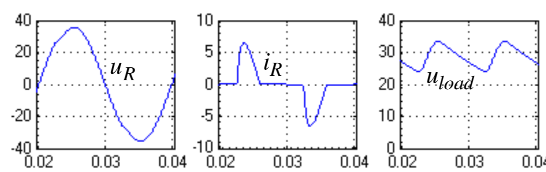

Fig.5. Nonlinear load connected directly to the grid (input voltage, input current, output voltage)

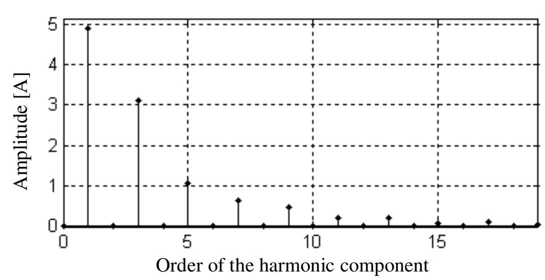

Fig.6. Harmonic content of the load current

After the active filter was connected and the system arrived on a steady state, the voltage at the load inputs is shown on Fig7.a, the drawn nonlinear current on Fig.7.b and the output load voltage on Fig.7.c. Comparing the results with the original situation one can conclude that the DC side of the nonlinear load will not be significantly influenced by the addition of the active filter.

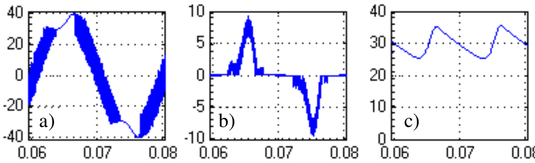

Fig.7. Voltage at nonlinear loads input, rectifier current, output voltage when APF is connected

Fig.8.a. presents the ideal AC voltage (blue) used on simulations and the total current drawn from the grid (green), which is sinusoidal and in phase with the voltage. Fig.8.b. presents the variation of the filter (red) and load (blue) currents during normal operation.

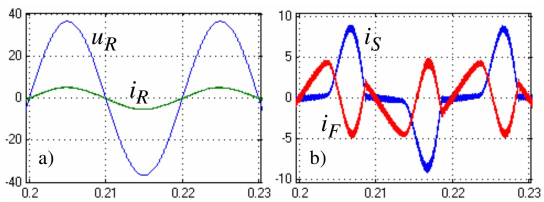

Fig.8. a) u_{AC} (blue), i_R (green) b) i_F (red), i_S (blue)

Fig.9. confirm that i_R contain only the fundamental harmonic component (50 Hz).

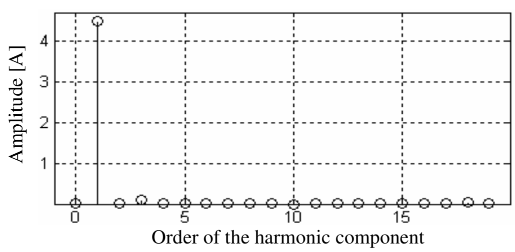

Fig.9. Harmonic content of the i_R current

The dynamic behavior of the voltage control loop can be observed in the following situation: at time $t = 0.15s$, R_{load} changes from 100Ω to 20Ω, and on $t = 0.3s$ R_{load} changes back to 100Ω.

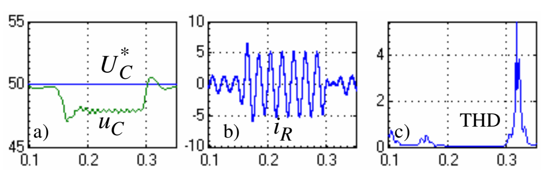

Fig.10. Dynamic variations of U_C, i_R, and THD at step changes in the load resistive component

Although the DC-link voltage controller is P type, the control loop will respond with overshoot, because of the delay produced by the filter on the DC capacitor voltage. The filter was used to block the 100 Hz component of the U_C (as seen on Fig.10.a) from $t = 0,2s$ to $t = 0,3s$) to enter in the currents control loop.

Fig.11. presents the evolution of all signals of interest in the circuit from the moment of power-up until the equilibrium of active power is attained. During this dynamic state the THD value cannot be controlled.

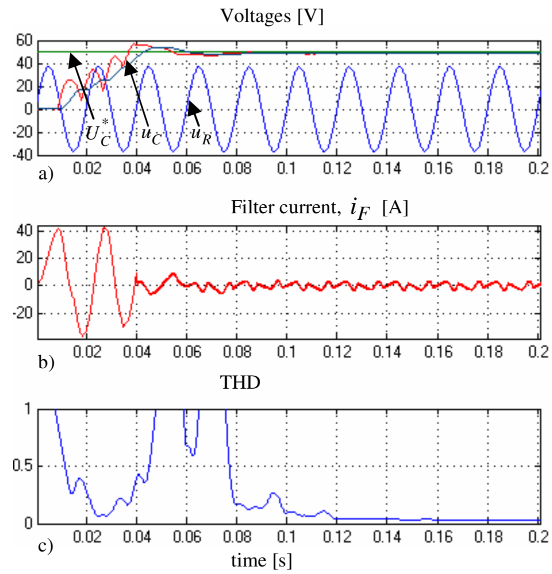

Fig.11. Dynamic variations of voltages, currents and THD of the circuit, at power-up

A steady-state error of the capacitor voltage will always exist, since the controller is P type. On Fig.11.a) the voltages chart show the AC voltage (blue), DC-link voltage reference, U_C^* (green), U_C (red) and filtered U_C (dark-green).

On Fig.11.b) on can be seen that the filter’s current is abnormally high. In fact, this current is a short-circuit current on the IGBT bridge because:

- DC capacitor is discharged,

- diodes from IGBT bridge will act as a ordinary rectifier bridge, and

- the IGBTs will conduct too because of the pulses generated by the pulse generator.

When the capacitor voltage reach a value higher than $u_{AC} \cdot \sqrt{2}$, the diodes from IGBT bridge stop conducting, and the circuit start to function properly.

The only practical solution is to keep all IGBTs blocked until the U_C reaches the necessary voltage.

3. EXPERIMENTAL RESULTS

3.1. The experimental platform

The platform was build on a small scale: power supply consist in a power transformer with 220V input and 26V, 5A maximum output and nonlinear load consist in a bridge rectifier with RC load. For experimentation purposes, resistor value can be changed between 100, 50 or 15 Ω ; capacitor value is fixed, $1000\ \mu F$. An advantage in using an isolation transformer between grid and load is that the inductance of the secondary windings will be used as inductance L in the filter.

The active filter was built on six different circuit boards, Fig.12, each one having a functional task:

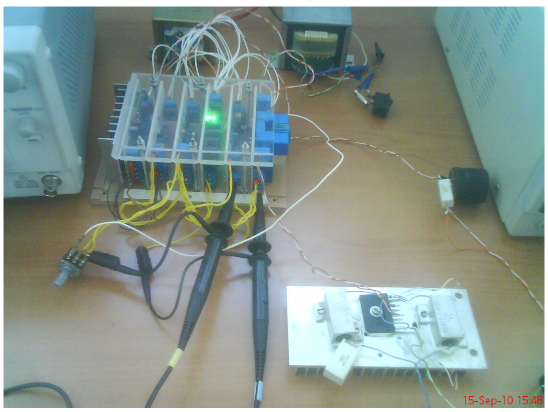

Fig.12. The experimental platform

- IGBT module with four IRGB4064DPBF (10A/600V), isolated driver (optocouplers and two IR2103) and an isolated voltage source; dead time is managed by the IR2103 circuit;

- pulse generator for the IGBT module: a triangular signal generator with fixed frequency, adjustable amplitude and two comparators with opposite output phases;

- "indirect control" module that compute the current error starting from voltage reference, capacitor voltage, current information and sinusoidal reference; analog circuits were used for subtract and multiply;

- PLL module that generate the sinusoidal reference signal; zero crossing of the mains voltage is used to synchronize a MAX038 signal generator and an operational amplifier is used to adjust the output voltage;

- transducers modules: LV25P (voltage) and LA55P (current) were used; The current transducer output is 1V/A, and the voltage transducer output is 0.05V/V.

- a power supply module, with stabilized ±5V and ±12V for the electronic circuits in the active filter.

The DC-link capacitor, $4700\ \mu F$, as well the power transformer can be seen in Fig.12.

Unlike the simulation model, where any signal can have unlimited high value, the experimental circuit imposes a numerical value smaller than *12*, since all the electronic circuits use ± 12V power supply, and we have chosen 1:1 scale between mathematic model and electronic circuit.

3.2. The experimental results

By connecting only the nonlinear load to the power source, on obtains the signals in Fig.13. Voltage at the loads input (blue) is strongly distorted by the nonlinear absorbed current (brown). The current measured THD is about 40%. This nonlinearity is propagated on the electrical grid through the power transformer.

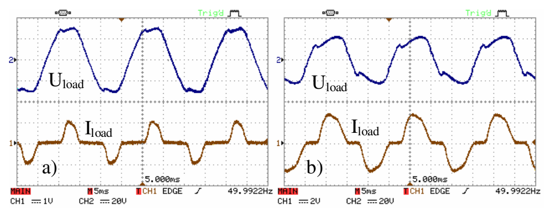

Fig.13. Load voltage and current, without APF
a) $R = 100\Omega$ b) $R = 15\Omega$

Connecting the load and active filter together on the output of the transformer, on obtains a sinusoidal current (brown) absorbed from the transformer and a voltage (blue) with lower distortions at the loads input, Fig.14:

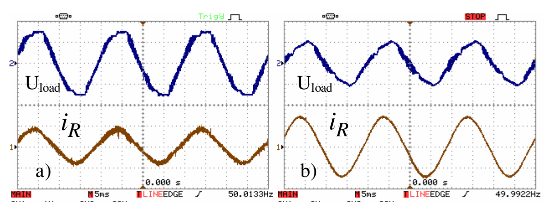

Fig.14. Load voltage and mains current, with APF;
a) $R = 100\Omega$ b) $R = 15\Omega$

Fig.15 presents the harmonic content of the current absorbed from the AC source by the nonlinear load, analyzed with FFT function of the digital oscilloscope GDS-2062. Can be observed that:

- in the case of uncompensated load all odd harmonics until the 17's are present, while

- the presence of APF will reduce the harmonic content only to the fundamental, as the simulation predicted.

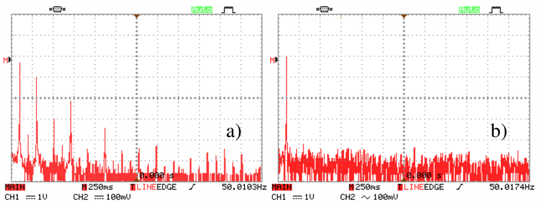

Fig.15. Harmonics content of the current, $R = 50\Omega$ a) without APF b) with APF

The current controller used in the active filter can be:

- a hysteresis controller that introduce in the i_R current a high frequency component, with wide spectrum (10kHz ÷ 20kHz), as seen on the Fig.16.a.

- a P controller followed by a PWM pulse generator; k_p is controlled from the amplitude of the triangular signal used on comparator stage. In this situation, the spectrum of the high frequency variations consists in fewer components (mainly the fundamental one), as seen on the Fig.16 a):

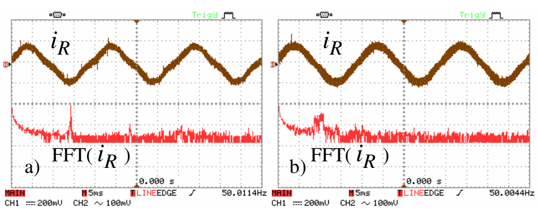

Fig.16. Spectral analysis of the high frequency harmonics (produced by the chopper) in the mains current; a) PWM with 17kHz b) hysteresis control

For the hysteresis case, the high-frequency harmonic content is presented on the Fig.16.b) and consist in signals from 2 to 20 kHz. The cases of maximum and minimum commutation frequency are presented in Fig.17. The bandwidth of the current error was imposed $0,4$ A to limit the commutation frequency below 20 kHz.

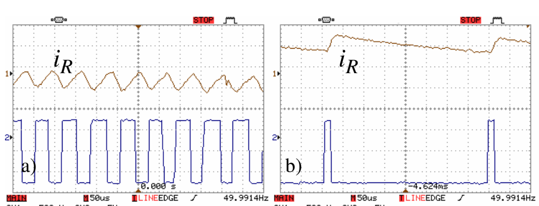

Fig.17. i_R current and command pulse for IGBT, hysteresis controller

The dynamic characteristics of the filter were observed by changing resistor value in the DC side of the load. Fig.18 does not show any visible phase error or overcurrent when changing the load resistor from 100 to 15 Ω .

As better seen in the Fig.19, the slow transition of the i_R current is due to passing energy from the DC capacitor in the filter to the load; as a result, the voltage across the DC capacitor lowers from 50 to 30 V. Since the voltage controller in the active filter is P type, a stationary error will always exist on the capacitor voltage; higher the load current, higher the voltage error for U_C .

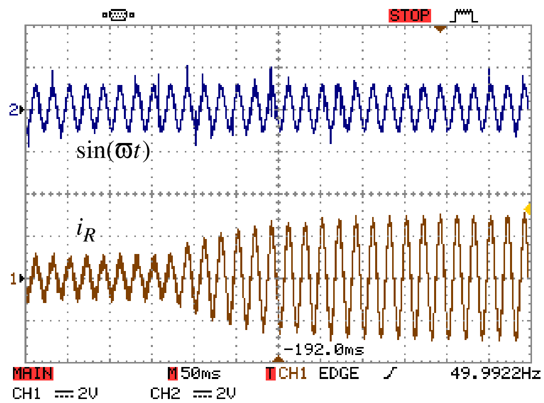

Fig.18. Reference voltage and i_R current, at load variations ($100\Omega \rightarrow 15\Omega$ at $t = 150ms$)

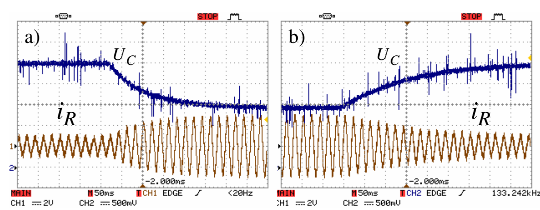

Fig.19. u_C (transducer output) and i_R current at load variations a) $100\Omega \rightarrow 15\Omega$; b) $15\Omega \rightarrow 100\Omega$

Simulations shown that without proper protection, at power-up the system will absorb current many times higher than the working one. In practice, Fig.20, the capacitor in the active filter charges right from the first semialternance of the AC voltage, and the amplitude of total current is acceptable:

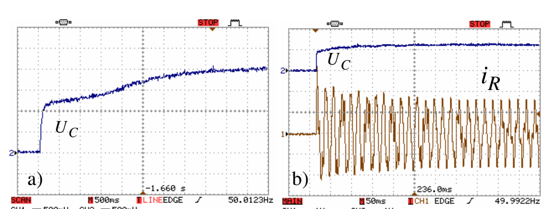

Fig.20. u_C (transducer output) and i_R at start-up, a) time to full charge; b) detail

A delay start of the IGBT driver was not necessary, due to the low power of the circuit, but we have chosen to delay the charge process of the DC capacitor to the reference voltage. This has been implemented by filtering U_C^* reference with a low-pass filter with $2\ s$ time constant. When the circuit is first powered the U_C^* will start from zero and slowly increase to the nominal value. This process takes more time than the time necessary for:

- the nonlinear load to arrive at the steady operation (the capacitor that follows the rectifier to be charged to the nominal voltage);

- settling the PLL loop that is used to generate the sinusoidal reference, Fig.21. This event can last up to $0{,}5\ s$ depending on the initial conditions, temperature and other variables.

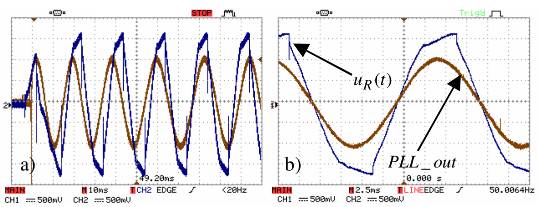

Fig.21. a) PLL startup phase error; b) signal used for synchronization and PLL output, steady state

Connecting the nonlinear load directly on the filters output is not advisable, since the nonlinear load usually consist in a low-frequency bridge rectifier and on the connection point between active filter and transformer (inductance L) the voltage is a high frequency, high amplitude rectangular signal (generated by the current controller); the mean value of this voltage is however close to the 50Hz harmonic. This will lead to increased power losses in the load diode bridge and may lead to abnormal operation of the load.

We have used an LC passive filter ($C = 330\ nF$, $L = 2\ mH$) to smooth the voltage for the nonlinear load.

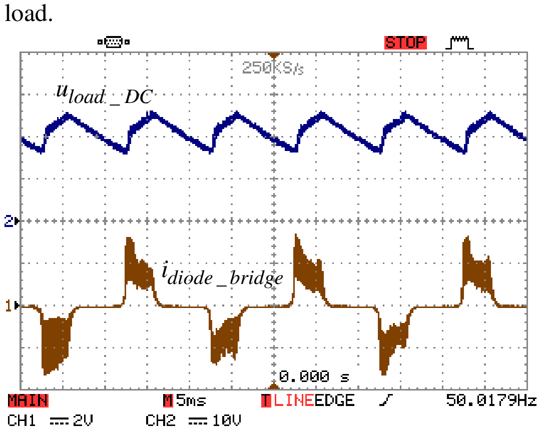

Fig.22. Voltage at the DC load and current through rectifier bridge, $R_{load} = 50\Omega$

Fig.14 shows the voltage at the bridge input, and Fig. 22 show the voltage on the DC side of the load and the absorbed current by the nonlinear load.

Signals are close to the original ones, so the addition of the active filter has negligible effect on the nonlinear load.

The total harmonic distortion (THD) parameter used frequently to describe the quality of the energy was measured: 40% for the current drowned by the nonlinear load, and about 4% when the active filter was used.

During operation of the circuit it is possible that the load to absorb nonlinear currents higher than the active filter can compensate. We observed the performance of the filter in this condition, by imposing a sufficiently low value for U_C^*. Fig.23 shows that the filter will operate properly and will compensate the nonlinearities until the energy stored in the capacitor it is no longer useful (DC-link voltage becomes too low). The shape of the i_R current (brown) is closer to the imposed sinusoidal reference, meaning a lower content of harmonics in the grids current:

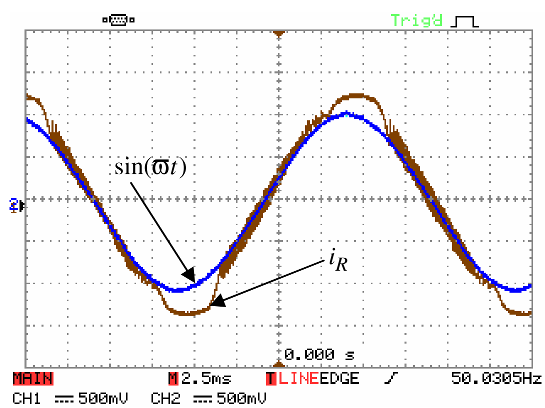

Fig.23. i_R current versus reference shape of the current, when nonlinear load absorbs more power than can be compensated by APF

4. CONCLUSIONS

The basic simulation model as well as the experimental small scale platform shows very good results in filtering the current of a nonlinear load with a shunt active filter based on indirect control. This method has the advantage of using only two transducers: one for voltage and one for current.

Experimental results were unexpected good even if the controllers used in the control algorithm allow stationary error on the controlled signal. Further analysis could consider some better controllers, with better dynamic characteristics.

The method of indirect control of an active power filter can be easily implemented on a low-power microcontroller since only basic mathematic operations are used to compute the current reference (FFT or any other signal analysis method implies not only specialized circuits and multiple mathematical operations, but a considerable delay too, on the computing the current reference). More, a digital implementation will offer facile solution to the start-up problems – shortcut currents in IGBT bridge, PLL settling time. (Abdusalama, et. all, 2009) presents one digital solution for obtaining the current reference.

Experiments have shown that the filter will continue to absorb sinusoidal current from the grid even if the grid's voltage is strongly distorted. The quality of the current drawn from the mains depends mostly on the quality of the sinusoidal reference used. When the mains voltage is distorted, a sinusoidal signal generator, synchronized with mains voltage (with PLL) must be used.

If a proper passive filter is used between nonlinear load and active filter, the load will not be disturbed by the active filter. Using high frequency signals to drive the IGBT inverter makes easier the filtering of high-frequency components of the current, both from the mains current and the loads current.

On experiments, the hysteresis controller performed better than the P one, even with high value for k_P; the simplicity and robustness of the hysteresis controller is proved to be a good solution when the switching frequency of the inverter is not critical. Chen *et al.* (2008) presented a method of dynamically adjust the bandwidth of hysteresis controller to limit the averaged switching frequency.

As a final result, an experimental value for THD of about 4% was obtained in experiments, while the simulations shown a possible 0.5%.This proves that the solution is applicable and can offer exceptional results.

5. REFERENCES

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