Annals of the University of Craiova, Electrical Engineering series, No. 38, 2014; ISSN 1842-4805

Control of a Single-Phase Active Filter Using Triangular Carrier and Hysteresis Switching in MATLAB/Simulink

Marian-Stefan Nicolae, Dinut-Lucian Popa, Ionut Daniel Smarandescu, Alexandru Tudorascu
University of Craiova, Faculty of Electrical Engineering, Craiova, Romania
nmarianstefan@yahoo.com, lpopa@elth.ucv.ro,
smarandescu.ionut@yahoo.com, tudorascu_alex@yahoo.com

Abstract— **The paper deals with MATLAB/Simulink models of single-phase active filters used for reducing the harmonic level and electromagnetic interference and to get compliance with the power quality standards. Four cases are modeled and studied in order to design and tune the best configuration for the active filter. Two of them are determined by the configuration of the load, which consists of a single-phase rectifier which feeds a resistive load, having a capacitive dc filter as a first setup and an inductive dc filter as the second setup. The single-phase active filtering system is based on a single-phase Voltage Source IGBT inverter with dc-link capacitor and a complete current control system that uses two different pulse-width modulation techniques. The two switching techniques, triangular carrier and hysteresis, determine the third and the fourth cases. The power quality and the existing standards are discussed, including the disturbances in a power system for a single-phase rectifier. The harmonics, how they are generated, and what problems they may introduce in the power system, are presented. The reference current for the power active filter is generated by the means of a resonant sinusoidal signal integrator filter implemented with a transfer function block. All simulations performed in MATLAB/Simulink validate the theoretical considerations but not all of them reveal a good agreement with the existing standards. The sinusoidal signal integrator integral coefficient it's tuned in order to obtain a good compromise between grid THD current and transient response to load change. The results are interpreted and centralized so they can be useful in possible hardware implementation.**

I. INTRODUCTION

Energetic is an area of particular importance that has grown stronger in the sense of the utilization of computers for different activities in generation, transmission and distribution of electricity to consumers. The use of data acquisition systems in various industrial processes has led to the development, diversification and improvement of all power system related components [1].

Continuous monitoring of power quality parameters has primarily a preventive function not allowing the consumers to affect the grid and, on the other hand, has the function of objective control for the observance of compliance with the contractual obligations (for both sides) to establish appropriate measures by national and international standards [1].

The requirements regarding power quality are very important. Different equipments are used to improve the power quality, e.g., transient suppressors, line voltage regulators, un-interrupted power supplies, passive power filters, active power filters (APF), and hybrid power filters [1]–[7].

Nowadays it is very common to observe the use of passive elements designed to correct the power factor or to drain some harmonic components from the load currents. However, in sensitive power systems, resonances involving the system's impedance with these passive filters may occur, resulting in an inadequate operation of the passive filter [1], [2].

Different mitigation solutions are currently proposed and used in practical applications to reduce the superior harmonics in power grids. Over the past few decades, the use of active filtering techniques has become more attractive due to the technological progress in power electronic switching devices, enhanced numerical methods, and more efficient control algorithms [3].

The paper proposes an active power filter as a method for monitoring and controlling the power quality parameters in single-phase systems in order to reduce the harmonic distortion generated by non-linear loads.

II. ASPECTS OF POWER QUALITY

A. Power Quality Problems

Power quality is a simple term, but it describes a variety of problems found in any electrical system [8], [9]. Fig. 1 provides an overview of power quality problems.

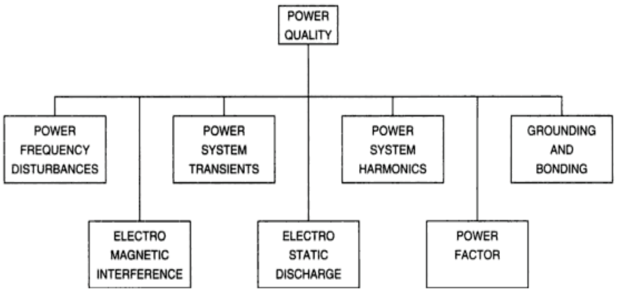


Fig. 1. Power quality concerns.

Several disturbances found in any electrical grid are: voltage sags; micro-interruptions; long interruptions; voltage spikes; voltage swells; voltage fluctuations; unbalanced voltages; electrical noise; harmonic distortion [10].

B. *IEEE 519-1992 Standard*

IEEE developed numerous standards regarding the power quality, among them the most appropriate being the Standard 519-1992 [9], [10].

IEEE Standard 519 - 1992 was first introduced in 1981 to give a direction concerning the approach of harmonics introduced by static power converters and other nonlinear loads, so that power quality problems can be avoided [9], [10]. Section 10 of the IEEE 519 – 1992 standard defines limits for different harmonic indices strongly correlated with the effects of harmonics. These prescribed limits are suggested values, and not absolute limits that cannot be overcome.

The defined indices are: total harmonic distortion of voltage - THDV; total harmonic distortion of current - THDI; the depth of the notch, the total area of the notch, and the dc bus distortion voltage by switching notches.

Because the ability of a harmonic source to produce harmonic distortion is depending directly to the system impedance, it is necessary to be measured by specifying the short-circuit current [9].

This standard specifies the limits of harmonic voltage at 5% for the total harmonic distortion, and at 3% from the fundamental voltage for a single harmonic. As for the THD of current, the limit is depending on the system impedance. Individual harmonic current weights are defined separately, in harmonic groups. For our modeled system, THDI can be maximum 5% [9].

The prescribed limits are applying only in steady state conditions and can be overcome in transient regimes by maximum 50 % [9].

III. MEASURES FOR THE POWER QUALITY IMPROVEMENT

A. *Single-Phase Power Filters*

By frequent use of power electronic converters, such as half-bridge or full-bridge rectifiers, fluorescent lamps, and so on, all being non-linear loads, the distorted currents and voltages may increase [1]. Extensive use of these non-linear loads leads to a power quality decrease, adversely affecting the power system performance. The presence of non-linear loads results in harmful effects for the power supply, leading to overheating cables, constant triggering of circuit breakers, noise, and so on.

In order to take corrective measures, several solutions have are available, the most effective in terms of quality being the active filtering [1], [2], [11].

One solution for eliminating most of the harmonic content is using a passive power filter containing filtering RLC cells tuned to the dominant harmonics. In single-phase systems, representatives are the 3rd, 5th, 7th, 9th, and 11th harmonics. If severe distortion exists, many cells may be needed making the solution impractical [1], [11].

The main requirement for an active power filter (APF) is to mitigate harmonics, but reactive power compensation is also possible. APF power factor compensation is continuous, rapid, and transient free. Passive filters always produce a certain amount of reactive power. This is not desirable when the load to be compensated already has a good power factor, as in this case, otherwise risk of wrong compensation can occur [11].

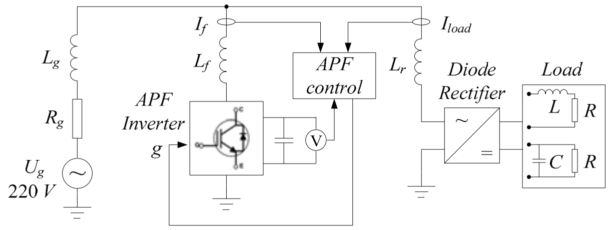


Fig. 2. Configuration of the single phase system, with the equivalent grid source, the active power filter and the non-linear diode rectifier load having a capacitive dc filter as a first setup and an inductive dc filter as the second setup.

Active filters are widely used for certain undesired disturbances, such as ripple switching, and in many applications, but mostly to eliminate the superior harmonics. In other applications active filters are more advantageous, due to their ability to control certain parameters by controlling power converters with PWM techniques in different ways, and by filtering of the superior harmonics up to the 40th order (in accordance with IEEE 519-1992 standard) [1], [9], [10].

B. *The modeled system configuration*

The modeled system configuration is depicted in Fig. 2. It consists of a single-phase rectifier which feeds a resistive load, having a capacitive dc filter as a first setup and an inductive dc filter as the second setup. The single-phase active filtering system is based on a single-phase Voltage Source IGBT inverter with dc-link capacitor and a complete current control system that uses two different pulse-width modulation (PWM) techniques.

C. *DC Voltage based PI Controller*

This theory is based on the dc capacitor voltage value feeding the voltage source IGBT inverter.

Depending on the dc voltage, the controller estimates the ideal current. The used controller is a proportional integral (PI) controller. The parameter adjustment is crucial in this theory because the controller response must be fast, allowing the active filter to also respond quickly to any change in the load [12].

The PI Controller is the most used in industry. It is used when: no need for a faster response of the system; high disturbances and electrical noise occur during operation; when system contains only one energy storage element (capacitor or inductor); there are delays of data transmission in the system [12], [14].

The PI controller's (Fig. 3) output is given by (1) [12]:

$$K_p\Delta + K_i\int \Delta dt \tag{1}$$

where Δ is the actual error measured when the actual signal is compared with the reference value.

A PI controller can be easily modeled in MATLAB/Simulink using Laplace operators:

$$C = \frac{G(1+\tau s)}{\tau s} \tag{2}$$

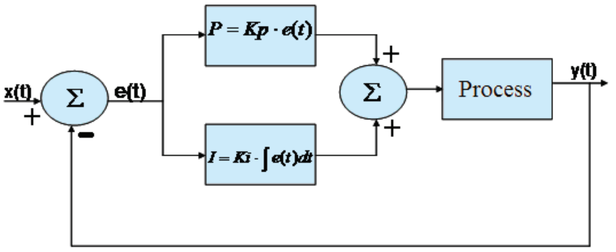
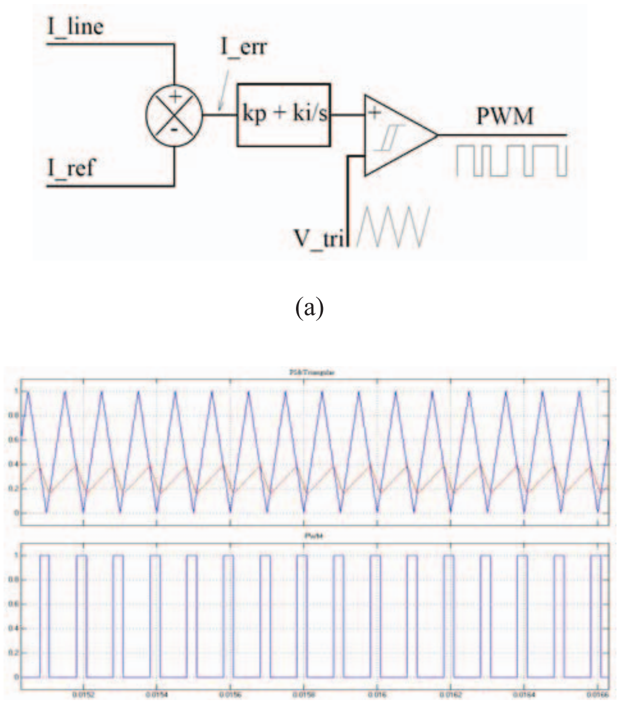


Fig. 3. The PI Controller.



(b)

Fig. 4. Generating PWM with a triangular carrier signal (a) scheme (b) waveforms of the triangular carrier and output of the PI controller (top) and IGBT gates output (bottom).

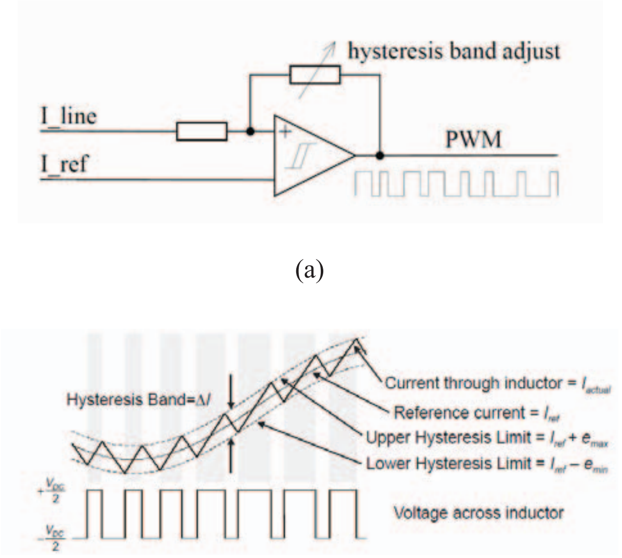
where: $G = K_p$ (“proportional gain”), $G/\tau = K_i$ (“integrative gain”) and τ = system's time constant.

Active filter's current can be controlled in many ways and the most effective method of generating the reference current for the active filter and the most adequate method for generating PWM signals must be chosen.

Two current controllers are selected for comparison, namely triangular carrier waveform and hysteresis controller respectively.

1) Triangular carrier waveform PWM converter switching control: compares the current error with a triangular waveform of a fixed amplitude and frequency (carrier). The error is processed by a PI controller before it is compared with the triangular waveform [12], [13]. The output of the PI controller gives the duty cycles. After comparing the error with the triangular signal, PWM gate signals are generated (Fig. 4). They are used afterward to control the converter.

1) Hysteresis PWM converter switching control: is used for switching power transistors when the current error exceeds a fixed value of the amplitude for the hysteresis band. This uses only one comparator with hysteresis on each phase (Fig. 5) [14]. In this case the switching rate is not constant, but it can be estimated. Error values imposed by the hysteresis band control the converter output ripple current and frequency [14].



(b)

Fig. 5. Generating PWM with a hysteresis controller: (a) scheme (b) waveforms of the current through inductor and voltage across inductor.

IV. SINGLE-PHASE ACTIVE FILTER SIMULATION

The single-phase active filter operation was modeled in MATLAB/Simulink. The general scheme is depicted in Fig 6. It is built using blocks from the SimPowerSystem library and the current controller is partially implemented in C Level 2 S-Function.

The system contains the nonlinear load with two different configurations (an uncontrolled single-phase diode full-bridge rectifier that supplies a resistive load, having a capacitive dc filter as a first setup and an inductive dc filter as the second setup), an APF composed by a coupling inductance *Lf*, a 4 quadrant IGBT inverter with dc capacitor as energy source and a low power RC switching ripple filter to suppress the high frequency harmonic components introduced by the inverter. The reference current of the active filter consist of a resonant sinusoidal signal integrator (SSI) filter tuned at the fundamental frequency [15], which is 50 Hz in Romania. It is built using an equivalent transfer function block. In the continuous-time domain, the transfer function of a SSI is given by [15]:

$$H_{SSI}(s) = k_p + \frac{2 \cdot k_i \cdot s}{s^2 + \omega^2} \tag{3}$$

where k_p is the proportional gain, set to unity, k_i is the integral gain and ω is the resonant angular frequency (set for the 50 Hz fundamental frequency).

The SSI integral coefficient it's tuned in order to obtain a good compromise between grid THD current and transient response to load change. Three values are selected and the results are centralized and interpreted.

In order to generalize the APF controller, the distorted regime compensation was simulated using two configurations of the load, which consists of a single-phase rectifier

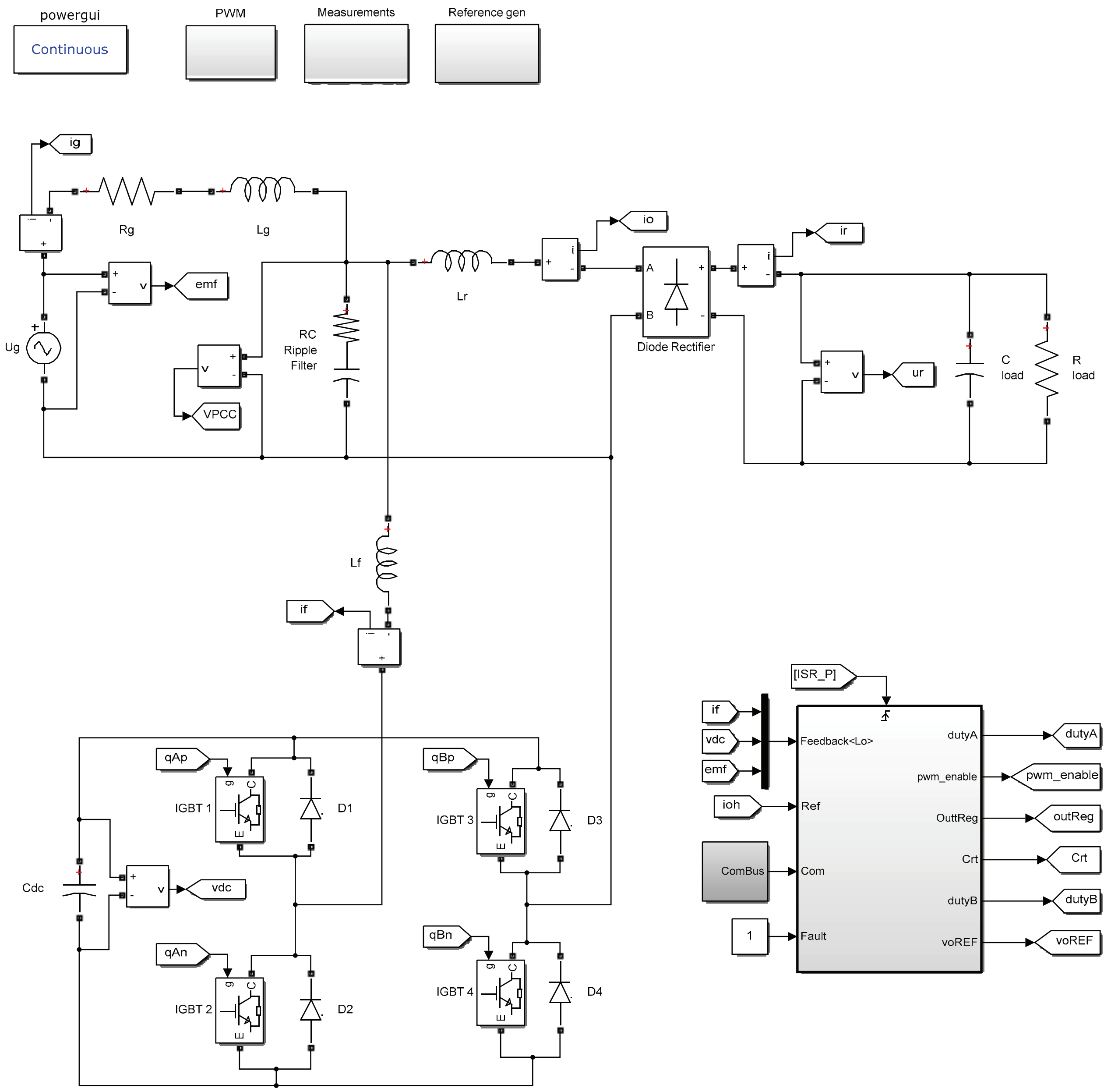


Fig. 6. Simulink model of the single-phase active power filter with capacitive filter on the dc side of the diode rectifier.

which feeds a resistive load, having a capacitive dc filter as a first setup and an inductive dc filter as the second setup (Fig. 2). The single-phase active filter is controlled in two different ways, one using triangular carrier wave and the other using hysteresis switching.

Triangular carrier wave methods is set to a switching frequency of 20 kHz and the hysteresis one has a variable frequency around this value, set by adjusting the hysteresis band (Fig. 5). The PWM converter of the active filter is H bridged (4 quadrant) to compensate the harmonics of positive and negative sequence.

The reference fundamental current is detected by means of a resonant SSI filter implemented with a transfer function block (Fig. 7). The reference current for the APF is obtained by subtracting the detected fundamental current from the load current.

To reduce the ripple in the grid current waveform introduced by the transistor's switching, one designed a passive RC filter with the cutoff frequency of 5 kHz.

This frequency was chosen considering the commutation frequency of 20 kHz for triangular carrier wave method and the frequency of the highest harmonic order

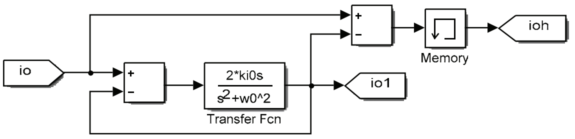


Fig. 7. The Simulink model of the fundamental and APF reference current detection method.

to be compensated. The cutoff frequency was computed with (4):

$$f_c = \frac{1}{2\pi RC} \tag{4}$$

A resistance of 1.44 Ω and a capacitance of 22 µF were used to set the cutoff frequency. The Bode plot for the RC ripple filter response and opperation when is introduced in the circuit is represented in the Fig. 8.

Te grid currents waveforms determined by the non-linear loads in the absence of a compensation equipment are depicted in Fig 9 and the harmonic weights are centralized in Table I. As it can be observed, the most significant is the 3rd harmonic (especially for capacitive filter), characteristic to single-phase systems (Fig. 11).

As for the fundamental current reference detection, the k_i integral coefficient of the SSI filter determines the behavior in transient states, but also the selectivity of the filter. The higher is k_i set, the higher is the response time, but the lower is the selectivity, allowing harmonic components with the fundamental current reference, also the higher is the phase delay, as it can be seen from the step and Bode plots in Fig. 12. The MATLAB step response tool returned a settling time of 0.39, 0.12 and 0.07 s corresponding to k_i coefficients of 10, 30 and 50. The simulations results are centralized in Table 2.

The triangular carrier PI controller has a lower bandwidth, being better suited for sinusoidal reference current, it cannot track the fast current changes in the APF reference current (Fig. 13) [16]. It delivers unsatisfying performances, none of the cases in which is used are satisfying the IEEE 519 limitations. The PI controller's bandwidth can be greatly improved by using P-SSI current controllers (Proportional-Sinusoidal Signal Integrator) [15].

TABLE I.
Type Sizes for Camera-Ready Papers

Harmonic order	THDI	
	Capacitive load	Inductive load
3	69.3	25.66
5	29.7	14.60
7	7.6	9.54
9	6.96	6.56
11	3.42	4.58
13	3.02	3.20

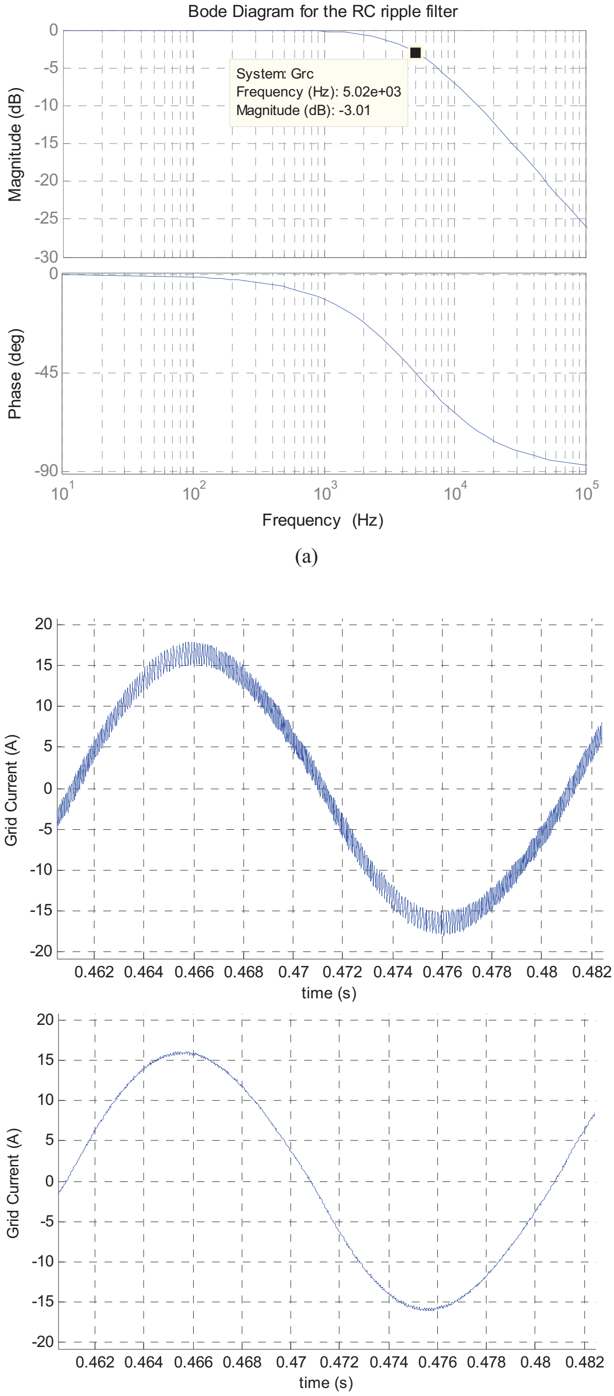
TABLE II.
Simulations Results

Current controller	$THDI_{ref}$ (%)		THDI (%)	
	Inductive load	Capacitive load	Inductive load	Capacitive load
Δ carrier, $k_i = 10$	0.65	1.76	6.09	6.16
Δ carrier, $k_i = 30$	1.96	5.19	6.22	6.29
Δ carrier, $k_i = 50$	3.26	8.62	6.71	7.96
hysteresis, $k_i = 10$	0.65	1.76	1.1	2.3
hysteresis, $k_i = 30$	1.96	5.19	2.15	5.44
hysteresis, $k_i = 50$	3.26	8.62	3.43	8.86

In contrary to the simple PI controller, the hysteresis one has a high bandwidth and tracks accurately the APF reference current.

The fundamental reference current is slightly lagging behind the PCC voltage vector (Fig. 13). This lag is corrected for the grid current by choosing the RC ripple filter capacitance larger (22 µF).

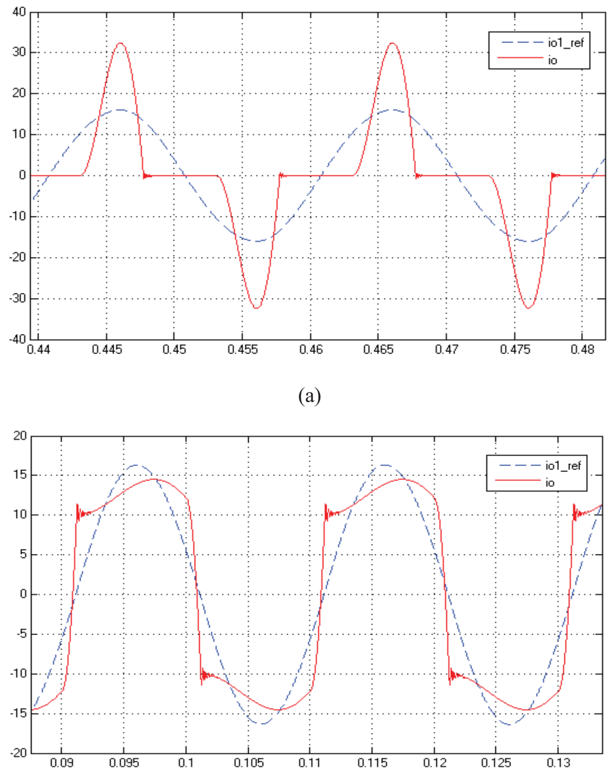
The Simulink models of the current controllers, namely hysteresis and triangular carrier wave PI are depicted in Fig. 14.



(a)

(b)

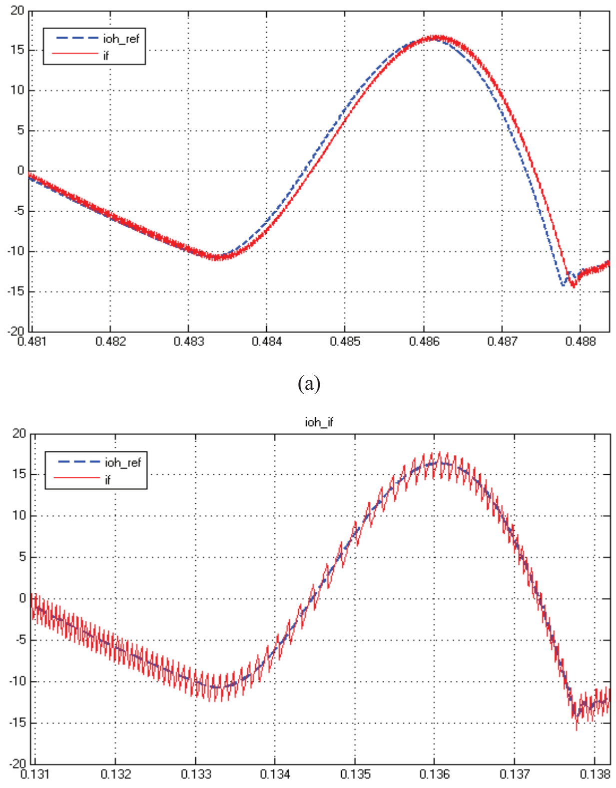
Fig. 8. Bode diagram (a) and operation (b) of the RC switching ripple filter.



(a)

(b)

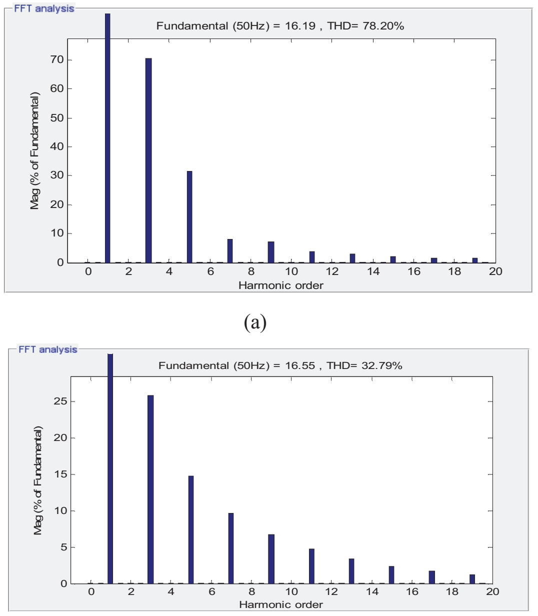
Fig. 9. Non sinusoidal current generated by the full-bridge diode rectifier with the capacitive (a) and inductive load (b) and the fundamental reference current.



(a)

(b)

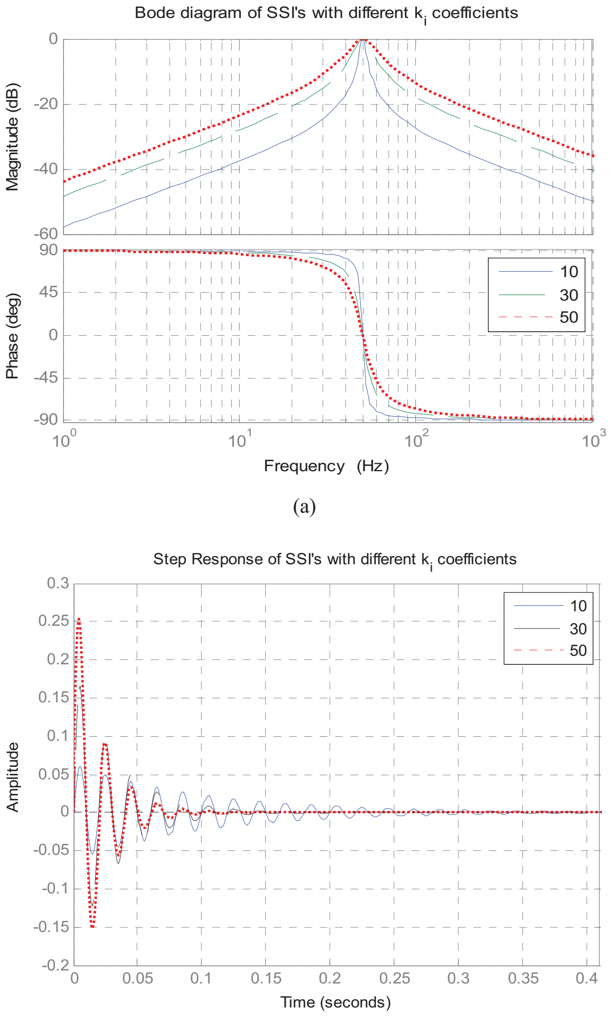
Fig. 10. Current injected by the APF and the reference current: (a) using trian-gular carrier wave PWM switching method; (b) using Hysteresis PWM switching method.



(a)

(b)

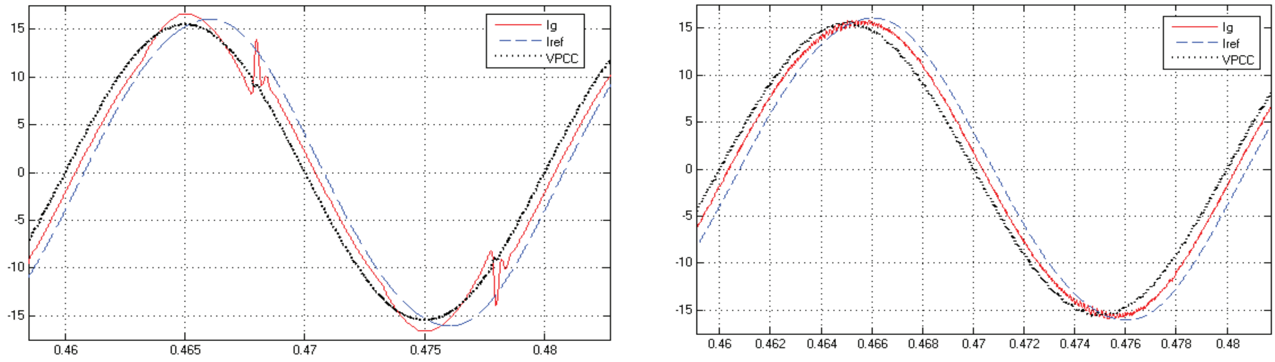
Fig. 11. Harmonic spectra of the load current: (a) capacitive load (b) inductive load.



(a)

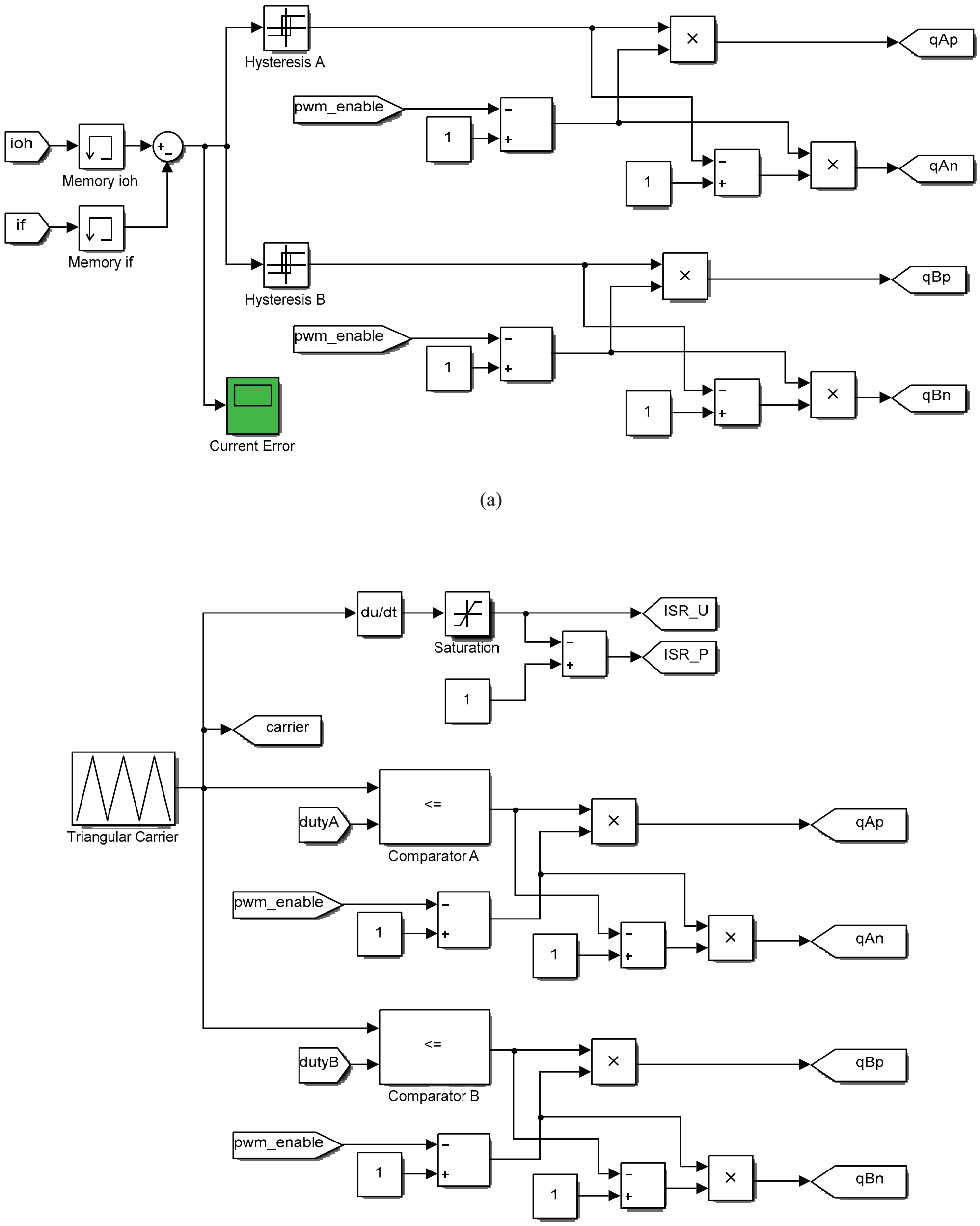
(b)

Fig. 12. SSI's response with different *ki* coefficients: (a) Bode plot; (b) step response.



(a) (b)

Fig. 13. Scaled PCC Voltage, the grid current *Ig* and the fundamental reference current *Iref* for: (a) PI controller; (b) hysteresis controller.



(b)

Fig. 14. Simulink model of the hysteresis PWM switching method (a) and the triangular carrier wave PWM switching method (b).

The only problem is with the current ripple, being higher and not constant in frequency components (Fig. 10). This leads to a higher rated RC ripple filter and possible noise emissions (acoustic and EMC).

The current ripple is 3 A without RC ripple filter for the hysteresis controller and 0.32 A for triangular carrier PI. After the RC filter is installed, the ripple drops to 1.25 A and 0.05 A respectively.

V. CONCLUSIONS

A single-phase active power filter was modeled in MATLAB-Simulink, for compensating the harmonic current injected by some common non-linear loads found in home appliances: a full bridge rectifier with capacitive and inductive filter.

The single-phase active filter operates satisfactory, reducing the THD in all simulated cases, to acceptable values, considering the high harmonic content introduced by the non-linear loads. Using a hysteresis controller provides better bandwidth, tracking accurately the APF current reference and providing the lowest THD for the grid current, satisfying the IEEE 519 requirements. The simple PI controller fails to accomplish these requirements, proofing that it is better suited for tracking sinusoidal references, so changes must be made, as in better tuning or changing to P-SSI controllers.

The reference current detection stage is tuned in order to obtain a good compromise between THD and response time, covering both situations (capacitive and inductive filter of the rectifier).

The results can be useful in possible hardware implementations.

ACKNOWLEDGMENT

This work was supported by the strategic grant POSDRU/159/1.5/S/133255, Project ID 133255 (2014), co-financed by the European Social Fund within the Sectorial Operational Program Human Resources Development 2007 – 2013.

REFERENCES

[1] M. S. Nicolae, A. Tudorascu, I. Smarandescu, " The Improvement of Power Quality Through a Single-Phase Active Filter using MATLAB/Simulink", Proceedings of International Conference on Applied and Theoretical Electricity ICATE 2014, Craiova, Romania, oct. 2014.

[2] H. Akagi, “Trends in active power line conditioners,” IEEE Trans. Power Electron., vol. 9, no. 3, pp. 263–268, May 1994.

[3] Muhammad H. Rashid, “Power Electronics Handbook”.

[4] B. Singh, K. Al-Haddad, and A. Chandra, “A review of active filters for power quality improvement,” IEEE Trans. Ind. Electron., vol. 46, no. 5, pp. 960–971, Oct. 1999.

[5] A. Sharaf, H. Huang, and L. Chang, “Power quality and nonlinear load voltage stabilization using error-driven switched passive power filter,” EEE Ind. Electron., vol. 2, 1995, pp. 616–621.

[6] W. R. Nogueira Santos, E. R. Cabral da Silva, C. Brandao Jacobina, E. de Moura Fernandes, A. Cunha Oliveira, R. Rocha Matias, D. Franca Guedes Filho, O. M. Almeida, and P. Marinho Santos, “The transformerless single-phase universal active power filter for harmonic and reactive power compensation,” IEEE Trans. Power Electron., vol. 29, no. 7, pp. 3563-3572, July 2014.

[7] C. Hsuand and H. Wu, “A new single-phase active power filter with reduced energy-storage capacity,” IEEE Proceedings on Electric Power Applications, , vol. 143, no. 1, pp. 25–30, 1996.

[8] IEEE Standard 1100-1992 - IEEE Recommended practice for powering and grounding sensitive electronic equipment http://standards.ieee.org/findstds/standard/1100-1992.html.

[9] T. Hoevenaars, K. LeDoux, and M. Colosino, “Interpreting IEEE Std 519 and meeting its harmonic limits in VFD applications”, May 2003.

[10] T. Blooming and D.J. Carnovale, “Application of IEEE Std 519-1992 harmonic limits,” IEEE IAS Atlanta section, Sept. 2007.

[11] P.-M. Nicolae, L.-D. Popa, M.-S. Nicolae, D.-G. Stanescu, I-D. Nicolae, "Performance comparison between active and passive power filters for a static excitation system in a power generator group: A MATLAB/Simulink approach," International Conference on Harmonics and Quality of Power (ICHQP), 2014 IEEE 16th, pp.112,116, 25-28 May 2014.

[12] H. Usman, H. Hizam, M. Amram, and M. Radzi, “Simulation of single-phase shunt active power filter with fuzzy logic controller for power quality improvement,” IEEE Conf. on Clean Energy and Technology, 2013.

[13] Z. Vukic and O. Kuljaca, “Lectures of PID controllers,” April 2002.

[14] David M. E. Ingram, Simon D. Round, " A fully digital hysteresis current controller for an active power filter", International Journal of Electronics, Volume 86, Issue 10, 1999.

[15] R. I. Bojoi, G. Griva, V. Bostan, M. Guerriero, F. Farina, F. Profumo, “Current control strategy for power conditioners using sinusoidal signal integrators in synchronous reference frame”, IEEE Transactions on Power Electronics, Vol. 20, No. 6, 2005, pp. 1402–1412.

[16] T. Santos, J. G. Pinto, P. Neves, D. Gonçalves, and J. L. Afonso, “Comparison of three control theories for single-phase active power filters”, 2009.

[17] L. Asiminoaei, F. Blaabjerg, and S. Hansen, “Detection is key – harmonic detection methods for active power filter applications,” IEEE Ind. Appl. Mag., vol. 13, no. 4, pp. 22–33, Jul./Aug. 2007.