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Controllable electronic load with energy recycling capability

***Abstract**. This paper presents the design and construction of a 3-phase controllable electronic load for high power tests allowing the recycling of the energy to the grid. The topology is composed by two electronic converters with a common DC- bus. One inverter draws from the grid a load current that can be configured with the harmonic and imbalance desired levels, and the other inverter is used to inject the energy into the grid with low losses. The control strategies and the current controller for both inverters are explained. Simulation and experimental results are presented.*

***Streszczenie.** W artykule omówiono układ sterowanego, 3-fazowego obciążenia elektronicznego dużej mocy, umożliwiającego recykling energii do sieci. Układ składa się z dwóch przekształtników elektronicznych – falowników, połączonych szyną DC. Podczas, gdy pierwszy falownik pracujący jako obciążenie pobiera z sieci prąd o zadawanych wartościach składowych zgodnych, przeciwnych i wyższych harmonicznych, drugi wstrzykuje pobraną energię elektryczną z powrotem do sieci z niskimi stratami. W pracy opisano strategię sterowania obydwu tych falowników. Przedstawiono wyniki badań symulacyjnych i eksperymentalnych (**Sterowane obciążenie elektroniczne z możliwością recyklingu energii**).*

Keywords: Electronic load, recycling energy, high power applications.
Słowa kluczowe: in this line the Editor inserts Polish translation of keywords.

Introduction

Energy power sources, such as uninterruptible power system (UPS) and generators, wind turbines, micro turbines, hybrid energy conversion systems, solar arrays and energy storage systems as batteries, ultracapacitors, superconducting magnetic energy storage coils, flywheels, need to be tested in a load bank to check the behaviour of the equipment and to improve its defective index, reliability and stability [1].

This load bank is usually designed with dissipative components, resistors, inductors and capacitors, which generate a lot of power losses, heat and few possibilities to carry out variable tests. For high power applications these power losses are unacceptable [2].

Electronic loads have been developed and commercialized [3] to extend the conditions of the test, as variable resistances, constant power, constant current, and constant voltage modes of operation, and even as non lineal loads [4].

Also, different types of electronic loads simulators [3] to test power supplies have been performed. Some authors [5,6,7] have developed control algorithms for these electronic loads simulators, achieving better performance and effectiveness.

In high power applications the most important aspect to improve is the energy recycling during the tests. Whit this objective, simulators have been developed considering the energy regeneration and trying to simulate a variety of load characteristics, and tests energy can be fed back to the power grid with little loss and high power factor. These simulators have been designed with a topology made by two electronics converters, with a common DC bus [8, 9]. Control strategies have been implemented, as repetitive control strategies [10] to manage these simulated devices, even showing experimental results when strategies are implemented in control platforms as DSPs.

Although there are some research works about active loads with energy recycling, only experimental small-scale prototypes or simulators can be found in the literature.

It is necessary to develop regenerative type active electronic loads to return the power to the grid. Several advantages of the regenerative type active load can be found, as follows:

- Highly energy-efficient system. The energy can be returned back to the utility grid, so a large amount of energy can be saved during test procedures for, mainly in case of high-power equipments.
- Compact size. The active regeneration scheme allows reduction on passive power components and associated cooling system. Thus the size can be reduced as compared to the conventional one.
- Flexible control design. The system typically requires a front-end ac-dc converter and a regenerative dc-ac inverter. The controller can be flexibly designed with dc link voltage either controlled by the converter or by the inverter [11].

Because of that, the development of a programmable device acting as an electronic load for high power applications with the possibility of choosing the current wanted to be demanded from the grid with different harmonic and imbalance levels is essential to allow variable tests.

This paper presents the design and construction of a 3-phase controllable electronic load with energy recycling, to be able to conduct tests for high power applications. A novel and simple control strategy is proposed. Simulations results at high power levels (100 kVA) and small-scale experimental results are included.

Programmable electronic load topology

Fig. 1 shows the electronic load scheme, composed by two electronic converters with a common DC bus. One inverter demands from the grid a load current while the other inverter injects energy into the grid. Some advantages of this active load is the energy saving and the simple control of DC bus.

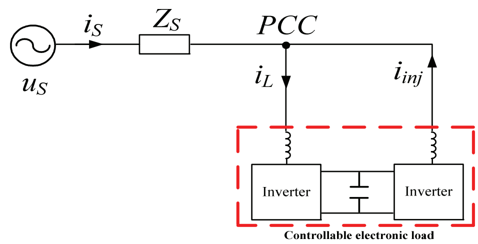


Fig.1. Active electronic load with energy recycling scheme.

The topology of the 3-phase AC electronic load with energy recycling is presented in Fig. 2. Each inverter leg is connected to the grid with a filter inductor, L_L *and* L_{inj}, *respectively*, and the middle point of the DC bus is connected to the neutral conductor directly.

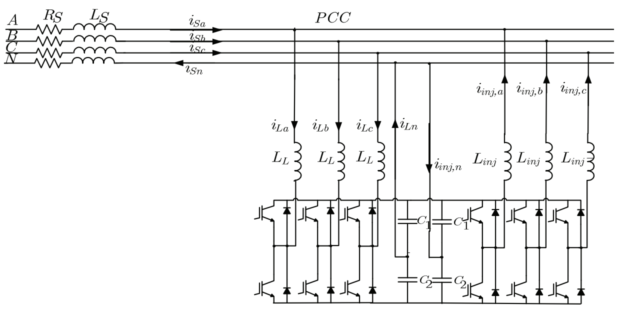


Fig.2. Active electronic load with energy recovery topology.

Control strategy

In this section the control strategy for each inverter used in the controllable electronic load is presented.

The first inverter is used as programmable load. To control this converter a friendly application has been developed which allows introducing the desired load current specifications to calculate the reference load current in the highlighted block in Fig. 3.

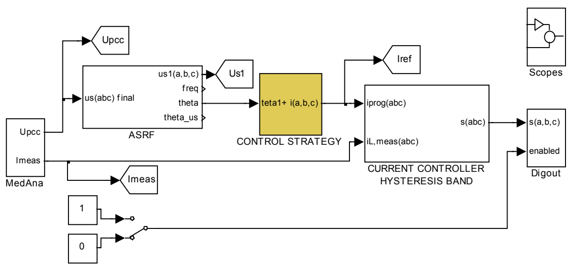


Fig.3. Programmable load control scheme.

The parameters to introduce are the *RMS* value, the harmonic order, the phase angle and the sequence for each component. With all of these parameters it is composed the reference load current with the required harmonic and/or imbalance levels. This block needs the angle of the positive sequence fundamental component of the voltage at the point of common coupling (PCC). It is achieved using the Autoadjustable Synchronous Reference Frame (ASRF) [12] block shown in figure 3, which needs the measurements of the PCC voltages $u_{PCC}(a, b, c)$.

The second inverter is used to inject the energy into the grid. To generate the reference injection current, it is necessary to analyze the circuit shown in Fig.2. Applying the First Kirchhoff law in the circuit, one has:

$$i_S + i_{inj} = i_L \,, \tag{1}$$

where: i_S – source current, i_{inj} – reference injection current, i_L – load current.

Despising the losses ($i_S \approx 0$) it is obtained:

$$i_{inj} = i_L \,. \tag{2}$$

Also the control of the DC bus is required. This control will be done by the injector device. For this reason a new term is included in (2):

$$i_{inj} = i_L - k_c(s)\,(U_{dcref} - U_{dcmean})\,u_{pcc_1^+} \tag{3}$$

where: U_{dcref} – DC bus voltage reference , U_{dcmed} – measured DC bus voltage, $u_{pcc_1^+}$ - positive sequence fundamental component of the PCC voltage, $k_c(s)$ – transfer function of a proportional-integer (PI) controller.

The block diagram of the injector control is displayed in Fig. 4.The injector reference current is obtained implementing equation (3) in the highlighted block of that figure.

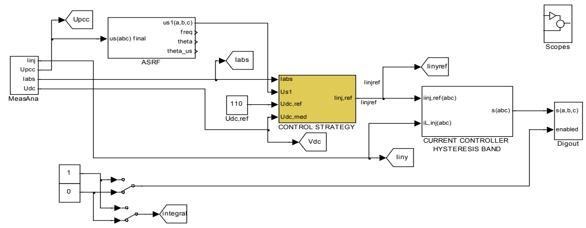


Fig.4. Injector equipment control scheme.

The control strategy of the global controllable electronic load requires the measurement of ten variables: U_{dc} , $u_{pcc}(a,b,c)$, $i_L\,(a,b,c)$, $i_{inj}(a,b,c)$.

Current controller

A hysteresis band (Fig.5 (a) and Fig. 5 (b)) has been employed as current controller in the programmable load, to track the reference load current with minimum error. This technique compares the reference load current with the measured load current and depending on the sign of the error the switching signals of the IGBT's are generated.

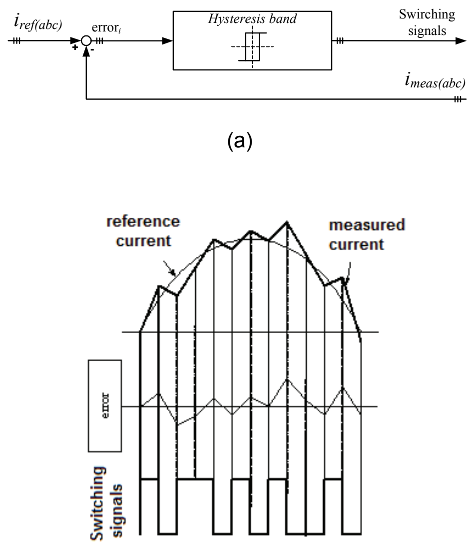


Fig.5 . Hysteresis band controller.

In case of the programmable load, from Fig. 2 it is easily determined that if the error in one phase is positive, a positive slope current is needed, so the upper IGBT of the corresponding inverter leg must be open and the lower IGBT must be closed. This operation mode is displayed in Fig. 6.

To control the injector the same hysteresis band has been used. Again, depending on the error ($i_{inj,ref}$-i_{inj}) the current controller generates the switching signal to control the IGBT's in order to increase or decrease i_{inj}.

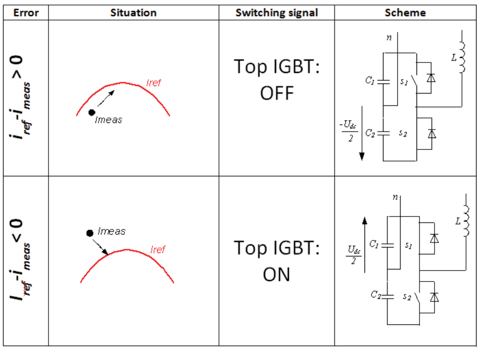


Fig.6. Operation of the hysteresis band to control the turning on and off of the switching of the inverters in the programmable load.

Simulation results

In order to test at high power levels the operation of the controllable electronic load, a 100 kVA active load with energy recycling has been simulated using *Matlab/Simulink*.

Three-phase three-leg with mid-point DC bus topologies sharing the DC bus, as shown in Fig. 2, have been implemented with the simulation parameters summarized in table 2.

Table 2.Simulation test parameters.

U_n	I_n	S_n	$f_{s(load)}$	$f_{s(inj)}$	L_L	L_{inj}	$U_{dc,ref}$
400 V	145 A	100 kVA	10 kHz	20 kHz	7 mH	3.5 mH	1000 V

where: U_n – nominal voltage, I_n – nominal current, S_n – nominal power.

The inductance value of the programmable load, L_L, has been selected in order to reduce the ripple due to the switching frequency. On the other hand, the inductance value of the injector, L_{inj}, has been calculated with the aim of tracking the reference current with minimum error, providing high derivative currents. For this reason, the injector inductance value is half of that of the load inductance and the injector switching frequency is twice that of the programmable load.

Simulations results of the controllable electronic load in case of ideal mains and distorted and unbalanced conditions are shown in the following sections.

A. Sinusoidal and balanced current in phase with PCC voltage

The parameters introduced into the data interface of the programmable load to generate the reference current are show in table 3.

Table 3. Reference current parameters of the programmable load.

Harmonic order	*RMS current (A)*	*Angle (rad)*	*Secuence*
1	145	0	+

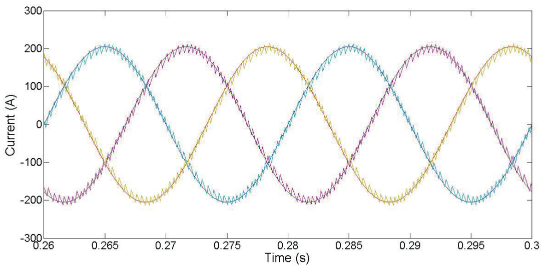


Fig.7. Reference and demanded load current in simulation test A.

The reference load current and the demanded load current are shown in Fig. 7, where it can be verified an appropriate tracking.

The reference current and injected current by the injector to recycle the energy into the grid are displayed in Fig. 8.

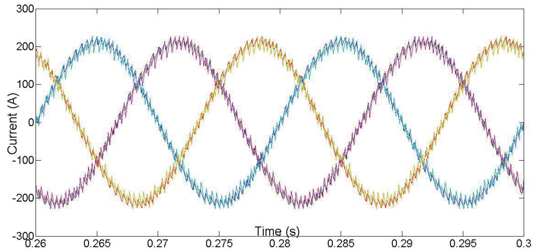


Fig.8. Reference and injected injector currents in simulation test A.

Finally, the RMS supply current is shown in Fig. 9. It can be concluded a very good performance of the controllable electronic load from this figure, since the energy recovery ratio is over 90%.

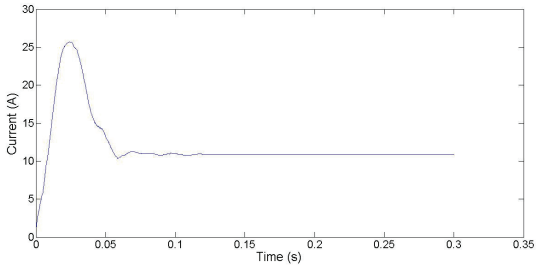


Fig.9. Supply RMS current in simulation test A.

B. Current with harmonic content (*h*=1, *h*=5 and *h*=7)

The reference current of the load in this case is programmed with individual harmonic distortion ratios of DA_5=20 % and DA_7=14.28 %, respectively. The RMS value of the fundamental component is 141 A. With these parameters, the reference load current and the demanded current are shown in Fig.10.

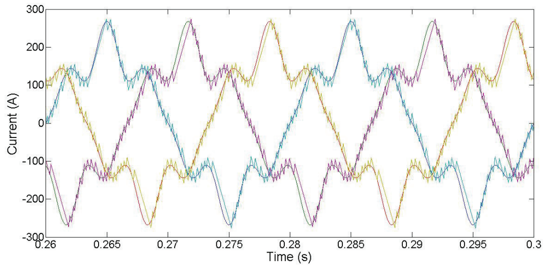


Fig.10. Reference and demanded load current in simulation test B.

Finally, Fig. 11 shows reference current and injected current by the injector. The RMS value of the source current is 10 A, achieving an energy recovery ratio similar to that obtained in the test A.

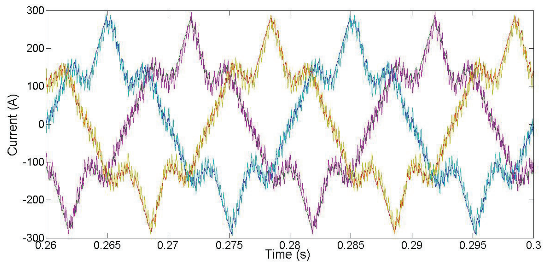


Fig.11. Reference and injected injector currents in simulation test B.

C. Unbalanced current

In this case, the controllable electronic load with energy recycling is tested with an unbalanced current. The unbalanced ratios are $I^-/I^+ = 22\%$ and $I^0/I^+ = 28.8\%$. The RMS value of the positive sequence component is 115 A. The reference load current and the demanded current are shown in Fig.12.

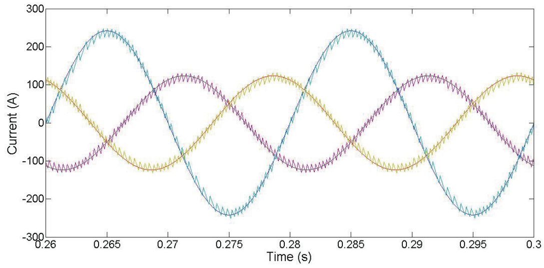


Fig.12. Reference and demanded load current in simulation test C.

In Fig. 13, it is displayed the reference current and injected current by the injector.

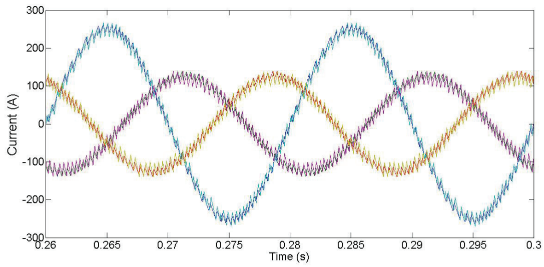


Fig.13. Reference and injected injector currents in simulation test C.

In this test the RMS source current is 8 A, so the attained recovery ratio is over 90%.

Experimental results

The proposed active load with energy recycling has been tested to verify experimentally the proper operation. These tests have been performed at low power levels. The electronic converter is a neutral-point-clamped voltage source inverter, as the on shown in Fig. 2, by *Semikron*. Hall effect sensors to measure the current in each leg and voltage sensors to capture the mid-point DC bus voltage and PCC voltage have been used.

XPC Target from *Matlab/Simulink* has been employed as control platform. Two industrial PCs have been used as Target to run the models in real time, equipped with data acquisition cards (DAQ's), and one PC is used as Host to control the other PCs.

The parameters in the experimental tests are shown in table 2. Due to XPC Target control platform limitations, the switching frequency have had to be decreased to 4 kHz.

Table 2. Experimental test parameters.

U_n	I_n	C_1	C_2	$f_{s(load)}$	$f_{s(inj)}$	L_L	L_{inj}	$U_{dc,ref}$
30 V	1.5 A	28.2 mF	28.2 mF	4 kHz	4 kHz	35 mH	35 mH	110 V

The operation of the controllable electronic load in case of ideal mains and distorted and unbalanced conditions are shown below in the following sections.

A. Sinusoidal and balanced current in phase with PCC voltage

The parameters introduced into the data interface screen of the programmable load to generate the reference current are show in table 3.

Table 3. Reference current parameters at load programmable.

Harmonic order	*RMS current (A)*	*Angle (rad)*	*Secuence*
1	1.5	0	+

The demanded current by the programmable load is shown in fig.14.

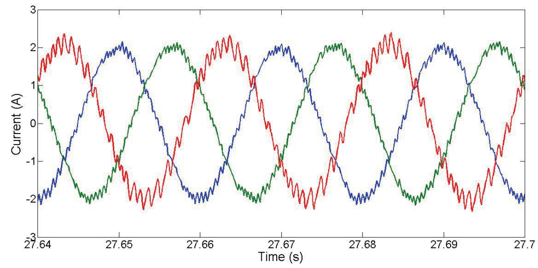
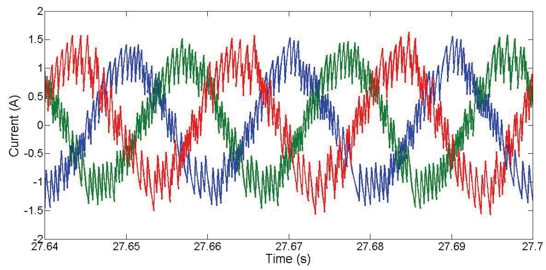


Fig.14. Demanded current waveform in experimental test case A.

The injector converter generates the reference injector current using equation (3). The current injected into the grid is displayed in Fig.15.



15. Injected current waveform in experimental test case A.

a)

b)

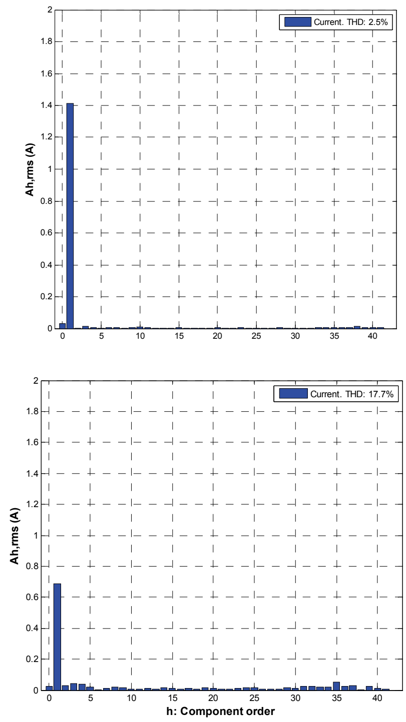


Fig.16. Experimental test case A: (a) Demanded current frequency spectrum. (b) Injected current frequency spectrum.

To evaluate the accuracy of the controllable load, the frequency spectrum applying the Fast Fourier Transform (FFT) both the demanded current and the injected current are analyzed. Total Harmonic Distortion (THD) is also calculated. Both spectra are displayed in Fig. 16 (a) and Fig. 16 (b), respectively. The lower fundamental component in the injected current is due to the power losses and the necessary current to control de DC bus voltage.

B. Current with harmonic content (*h*=1, *h*=5 and *h*=11)

The reference current of the load in this case is programmed with an individual harmonic distortion of DA_5=23 % and DA_{11}=15 % respectively. The RMS value of the fundamental component is 1.3 A. With these parameters, the demanded current by the programmable load is shown in Fig.17. The current injected into the grid is displayed in Fig.18.

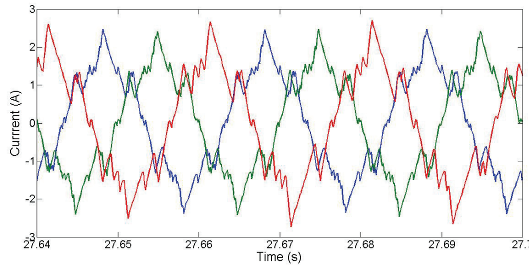


Fig.17. Demanded current waveform in experimental test case B.

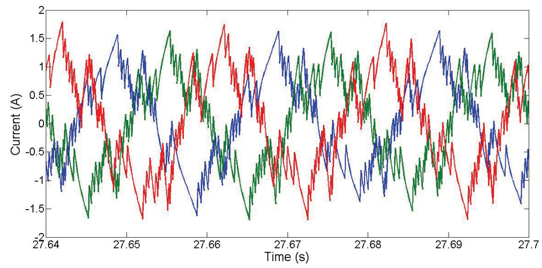
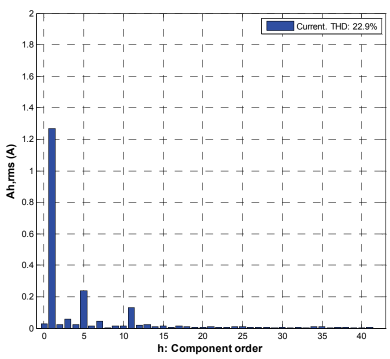


Fig.18. Injected current waveform in experimental test case B.

a)



b)

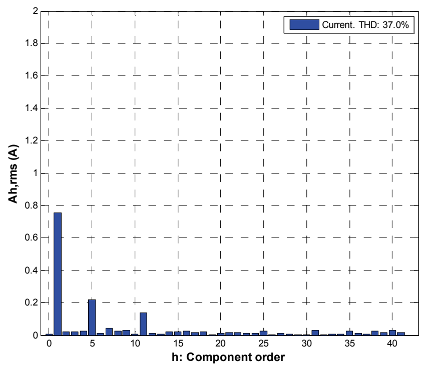


Fig.19. Experimental test case B: (a) Demanded current frequency spectrum. (b) Injected current frequency spectrum.

To evaluate the accuracy of the controllable load in this case, the frequency spectrum applying the Fast Fourier Transform (FFT) for both the demanded and injected current are analyzed. These spectra and the value of THD are shown in Fig. 19.

C. Unbalanced current

In this test the load contains unbalance (I^-/I^+=32.66% and I^0/I^+=14.4%), being the RMS value of the fundamental component 1.47 A. The demanded current by the programmable load is shown in Fig.20 and the injected current by the injector is displayed in Fig. 21.

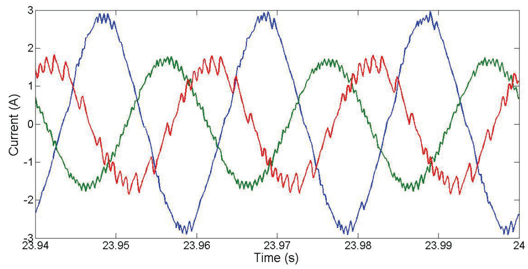


Fig.20. Demanded current waveform in experimental test case C.

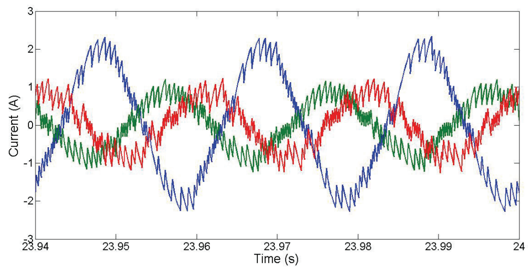
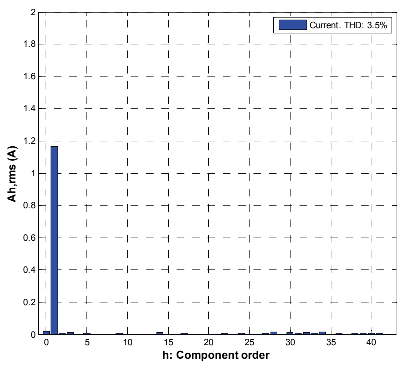


Fig.21. Injected current waveform in experimental test case C.

a)



b)

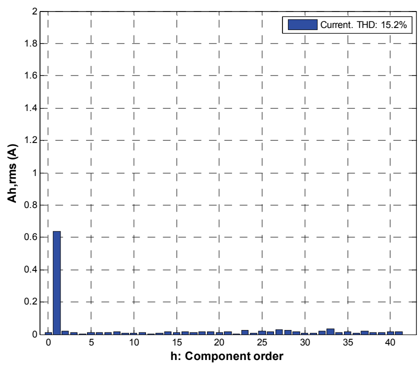


Fig.22. Experimental test case C: (a) Demanded current frequency spectrum. (b) Injected current frequency spectrum.

The frequency spectra and Total Harmonic Distortion (THD) of the demanded and injected current are presented in Fig. 22. Again, the lower fundamental component in the injected current is due to the power losses and the necessary current to control de DC bus voltage.

Conclusions

An electronic load with energy recycling has been presented in this paper. It is formed by two inverters sharing the DC bus, being one inverter in charge of demanding the programmable load current and the other one responsible for injecting the energy into the grid. A novel control strategy is proposed for the injector equipment with the objective of mnimizing the current demanded from the grid to the power losses in the internal resistance of inductors and semiconductor devices. The load can be programmed to demand single-phase and three-phase sinusoidal, distorted or unbalanced currents with the aim of testing not only series equipments, but parallel equipments such as active or hybrid power filters. Simulation results in case of high power applications are presented to verifiy the proper operation of the controllable load. Finally experimental results in a small-scale laboratory prototype are included.

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