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Transformerless Series Active Power Filter to Compensate Voltage Disturbances

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Keywords

Power Quality, Voltage Source Inverters, Active Filter, Harmonics, DSP, IGBT.

Abstract

This paper presents a transformerless topology of series active power filter with capability to protect sensitive loads against harmonics, sags, swells and unbalances of the power system voltages. The proposed topology is constituted by three isolated H-bridge with a voltage source at the DC side. The series active power filter has been studied with the help of PSIM (Power Simulation software) and simulation results are presented. A laboratory prototype is under development and experimental results are shown.

Introduction

The increasing use of rectifiers, thyristor power converters, arc furnaces, switching power supplies and other non linear loads is known to cause serious problems in electric power systems [1-3]. These devices are responsible by the contamination of the system currents with harmonics of various orders, including inter-harmonics. Harmonics current circulating through the line impedance produces distortion in the system voltages. Besides, since many of the loads are single-phase ones, voltage unbalance is also very common in three phase power systems [2]. The distortion and unbalance of the system voltages causes several power quality problems, including the incorrect operation of some sensitive loads [4,5]. Fig. 1 presents a diagram that illustrates the distortion of the system voltages.

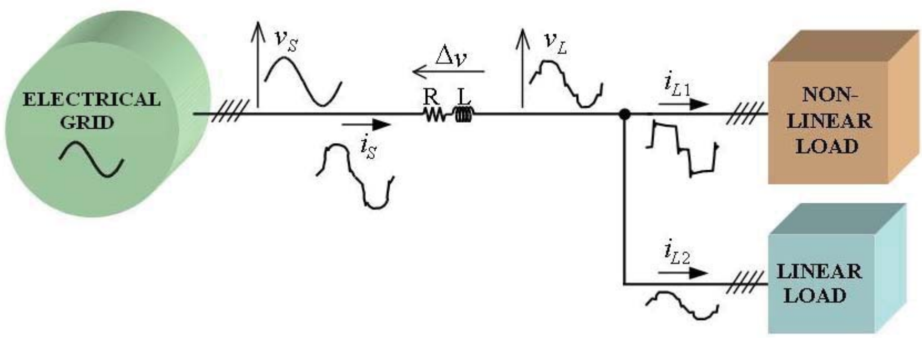

Fig.1 – Causes of the system voltages distortion.

In the last years, research engineers have presented various solutions based in power electronics to compensate power quality problems [6-12]. The utilization of equipments like Shunt Active Power Filters, Series Active Power Filters and Unified Power Quality Conditioners (UPQC) presents significant advantages to the power system. In this way, the research of new topologies and new control algorithms to improve the performance and capabilities of these equipments is object of great interest [13,14].

Series active filters work as voltage sources connected in series with the electrical grid, and they can compensate voltage harmonics. Three-phase series active power filters can also compensate unbalances in the phase voltages [12]. If the DC link of the power inverters is connected to other power supplies, the compensation capabilities of the series active power filter increases, allowing also the compensation of voltage sags, voltage swells and flicker [10,11].

Series Active Power Filter Topology

The hardware of the transformerless series active power filter is constituted by three independent IGBT H-bridges with an LC passive output filter. To compensate some of the voltage disturbances, namely sags, the series active power filter injects active power, so the DC link of each H-bridge is connected to a DC power supply. To prevent short-circuits between the system phases, three isolated power supplies are required. Fig. 2, shows the block diagram of the proposed transformerless series active power filter. The nonlinear load block presented in this figure, represents the loads of nearby electrical installations or other loads of the same facility that don't need to be protected by the series active power filter. This block is used to distort and unbalance the system voltages trough the line impedances representing a real situation. In order to control the series active power filter, six voltage sensors are required. Three of the six voltage sensors are used to acquire the three system voltages and the other three sensors are used to acquire the load voltages.

The three phase series active power filter is composed by three similar IGBT H-bridges. Each of the bridges works as a voltage controlled, three level voltage source inverter. Although the series active power filter control theory is applied to a three phase system, each of the H-bridges works independently. In other point of view the proposed topology can be understood as three single phase series active power filters, with a single three phase controller (that allows the phase voltages balancing).

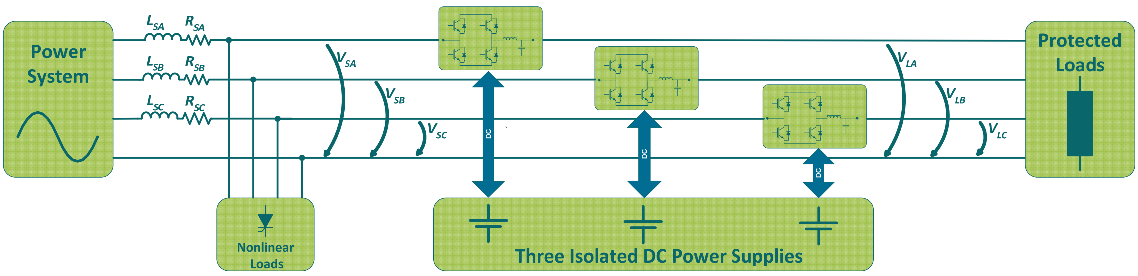

Fig. 2 – Block diagram of the transformerless series active power filter.

Series Active Power Filter Control Theory

Several algorithms have been implemented in order to control the operation of the series active power filter. The first algorithm (a digital Phase Locked Loop - PLL) is responsible by the synchronization of the controller with the positive sequence of the system voltages. To perform this operation, the system voltages (v_{SA}, v_{SB} and v_{SC}) are translated to the *α-β-0* reference frame through the Clarke transformation. After the transformation, two imaginary currents (i_α and i_β) are generated with a phase shift of 90º from the v_α and v_β voltages respectively. Then the accumulation of the products from $v_\alpha.i_\alpha$ and $v_\beta.i_\beta$ is minimized by a proportional-integral controller and integrated, resulting in a sawtooth signal. Through the calculation of the sine and cosine values of the sawtooth signal, the synchronizing signals (two sine waves with unitary amplitude pll_α and pll_β) representing the positive sequence of the system voltages in the *α-β-0* reference frame are obtained. These synchronizing signals are then translated to the *a-b-c* reference frame trough the inverse Clarke transformation, and multiplied by a constant value to obtain the theoretical value that the load voltages should have. The compensation voltage references are achieved by the calculation of the difference between the system voltages and the theoretical value of the load voltages. Fig. 4 shows the control algorithm of the series active power filter.

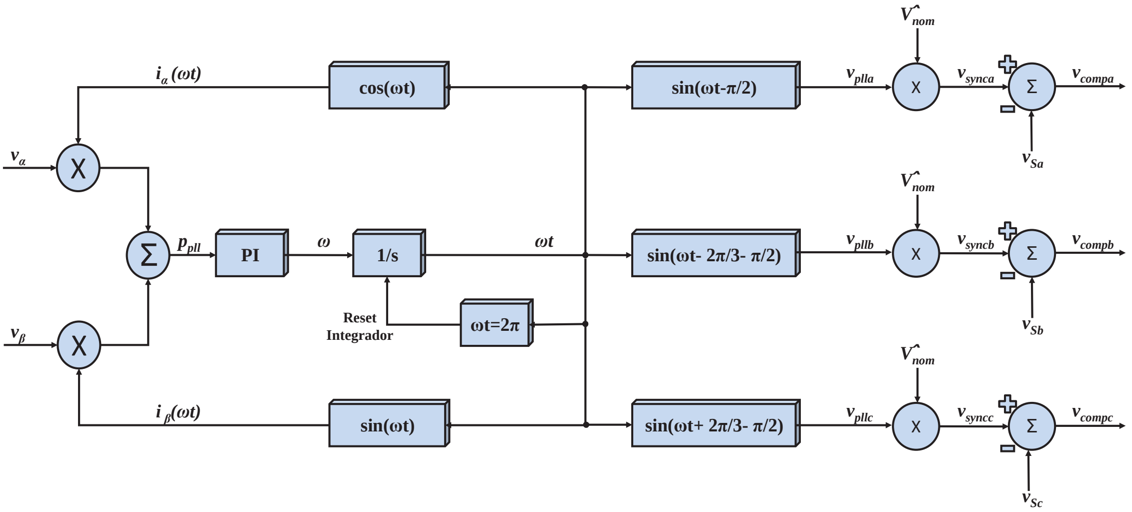

Fig. 3 – Series active power filter control algorithm.

Simulation Results

In order to verify the proper operation of the proposed topology and its control algorithms, some simulations were carried out with PSIM. A circuit similar to the model presented in Fig. 2 has been implemented in the PSIM environment. The control algorithm has been implemented through the use of *dll* files written in visual C++ and compiled to be compatible with the PSIM *dll* pattern. Fig. 4 a) shows the load voltages, Fig. 4 b) shows the system voltages and the voltages produced by the series active filter. Table 1 presents some information about the waveforms of Fig. 4.

a) System voltages b) Load voltages and Filter voltages

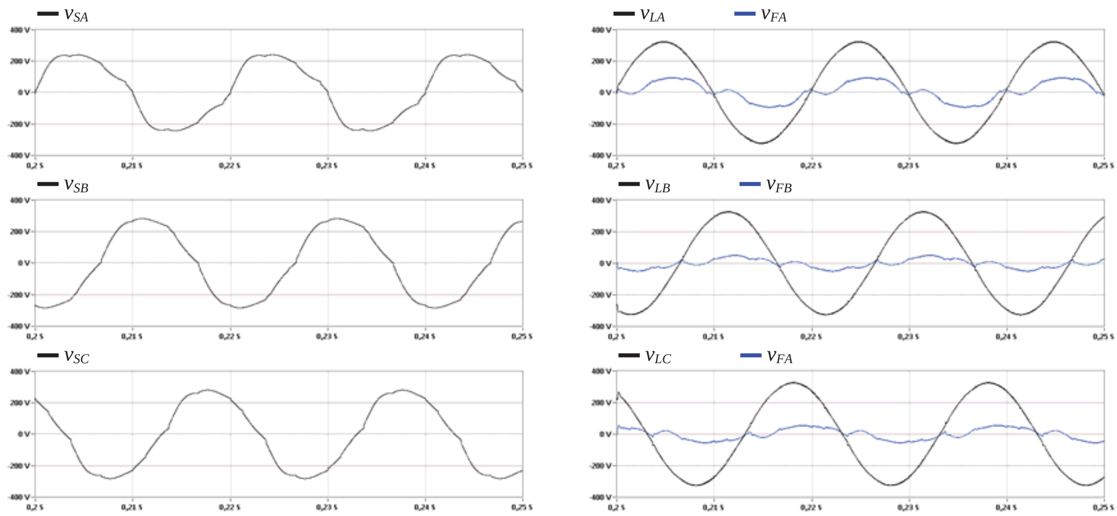

Fig. 4 : Simulation results of the series active power filter: a) System voltages; b) Compensated load voltages and filter voltages.

As it can be seen in Fig. 4, the series active power filter compensates the voltage harmonics, voltage unbalances, and sags. The protected loads, consequently, are supplied with three sine wave voltages with a phase shift of 120º and constant amplitude.

Table 1: Characteristics of the voltage waveforms presented in Fig. 4.

SIGNAL	RMS (V)	MAX (V)	THD (%)
v_{SA}	179	319	13.2
v_{SB}	208	283	6.9
v_{SC}	204	281	6.8
v_{LA}	230	325	1.9
v_{LB}	231	328	1.3
v_{LC}	231	327	1.2

To verify the behaviour of the proposed topology and its control algorithms in a more realistic scenario, a more meticulous simulation model has been developed. The new model takes in account the voltage and current sensor scales, the processing time of the DSP, the use of integer variables instead of double precision ones and other practical implementation issues like ADC resolution, sampling frequency, PWM limits and interlock times. Also the line impedance and the loads have been modelled to be very similar to the 90 V three-phase power system available to test the laboratory prototype of the Active Power Filter. The use of an accurate simulation model is very helpful to adjust control parameters, like the gain of PI controllers, and to prevent implementation errors. The use of the C/C++ program language in the simulation model allows the safe development and validation of controller functions. With some precautions, the controller functions developed to PSIM can be used in the DSP development environment. Fig 5 presents the results obtained with the 90 V power system model.

a) System voltages b) Load voltages and Filter voltages

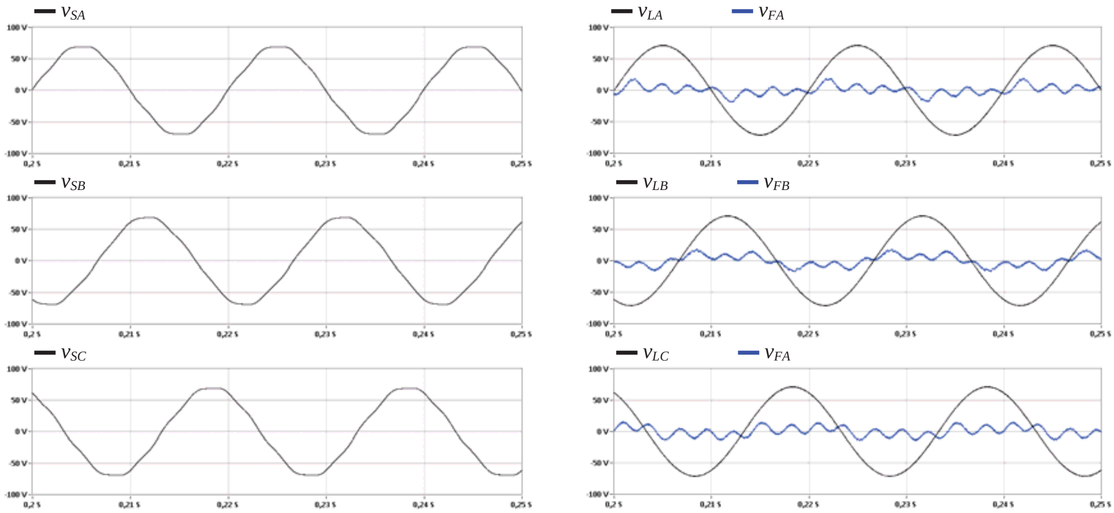

Fig. 5: Results obtained with a simulation model for the power system of the laboratory: a) System voltages; b) Load voltages and Filter voltages

Experimental Results

A laboratorial prototype of the presented transformerless series active filter topology has been developed. The three H-Bridges are constructed with six SKM145GB066D SEMIKRON dual IGBT modules. The digital controller has been implemented in a Texas Instruments TMS320F28335 DSP, with the help of the IDE integrated development environment Code Composer Studio (CCS). Fig. 6 presents the experimental results achieved with the laboratory prototype, and registered with a Yokogawa DL716 digital scope. Fig. 6 a) shows the system voltages. Fig. 6 b) shows the compensated load voltages and the voltages produced by the series active power filter.

To evaluate the performance of the series active power filter, a Fluke 434 power quality analyser was used to measure and register the system voltages and the load voltages, which are presented in Fig. 7. As it can be seen in this figure, the series active power filter compensates almost all of the harmonic content of the system voltages, reducing the voltage THD from about 3 % to less than 1 %. The series active filter also restores the voltage amplitude to 90 V line-to-line (52 V line-to-neutral).

a) System voltages b) Load voltages and Filter voltages

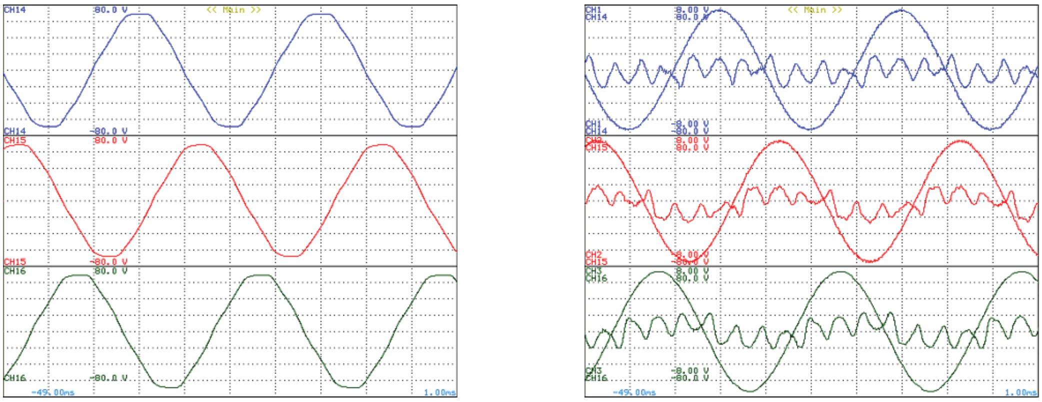

Fig. 6: Experimental results registered with a Yokogawa DL716 digital scope:
a) System voltages; b) Compensated load voltages and series active filter voltages.

System Voltages Load Voltages

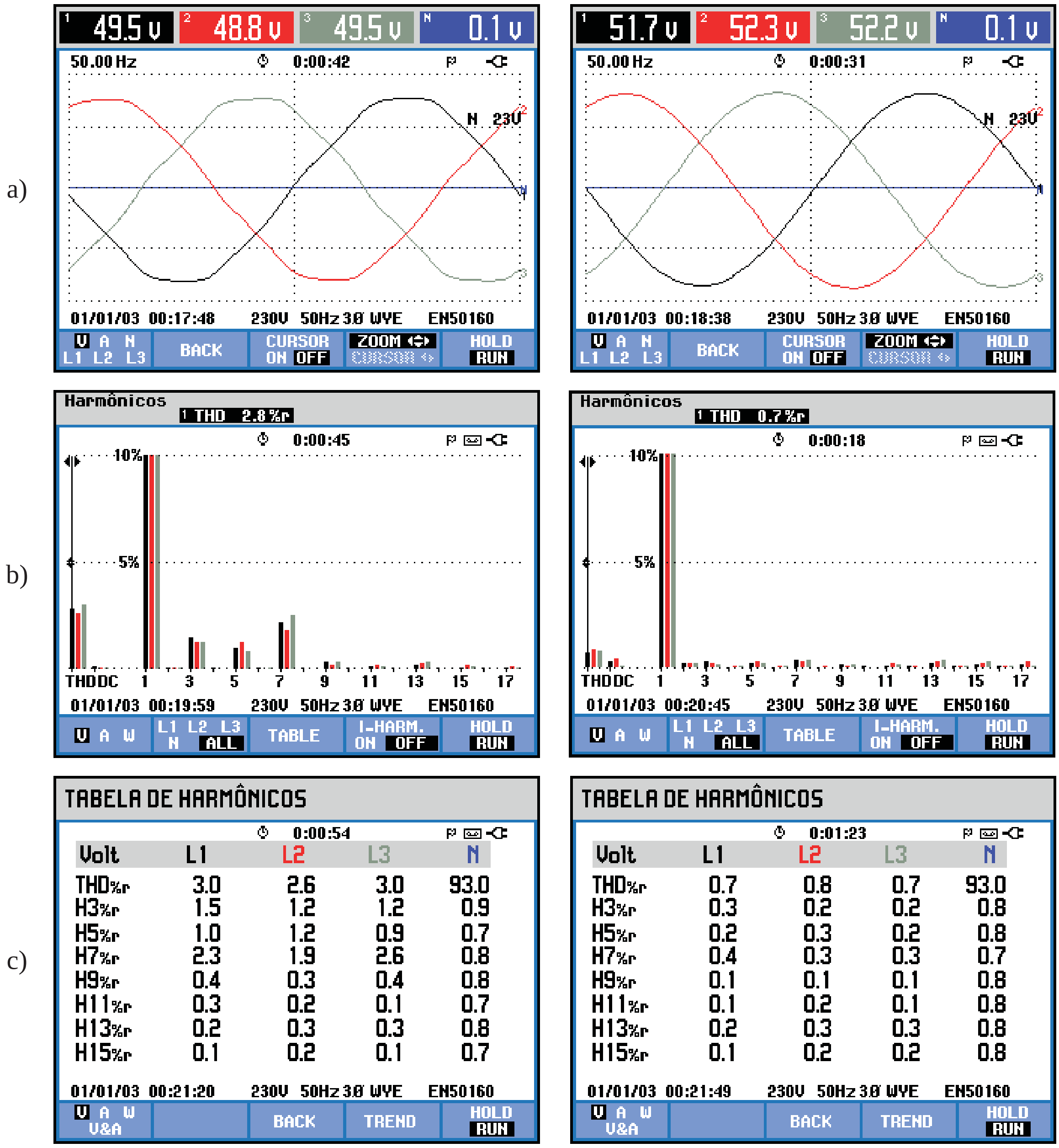

Fig. 7: Experimental results registered with a Fluke 434 power quality analyser: a) Voltage waveshape; b) Harmonic spectrum; c) Table of harmonics in percentage of the fundamental.

Conclusions

This paper presents a transformerless topology of series active power filter with capability to compensate voltage harmonics, sags, swells and unbalances. The proper operation of the presented topology and control algorithms is validated trough computer simulations results, developed with PSIM software. A laboratory prototype has been developed and experimental results are shown. The presented results show a good performance of the developed transformerless series active filter working in steady state conditions. The next step of this work is to construct a test workbench to assess the prototype in more adverse conditions, and also to evaluate the behaviour of the transformerless series active power filter in transient conditions.

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