Implementation of a power electronics workstation for power quality studies

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***Abstract*— This paper discusses an implementation of a power electronics workstation to be used in power quality studies. Two techniques of rapid control prototypes and hybrid simulations are applied to power electronic devices like active power filters, power switched sources and adjust speed drivers for testing power theories like p-q theory and generalized power tensor theory. A summary description of the workstation modules and the original contributions in power quality analysis are also presented.**

***Index Terms*— Active power filters, applied research, laboratories, power electronics, power quality and power switched sources.**

I. INTRODUCTION

Active power filters and nonlinear loads have common Power Electronics (PE) circuitry, one device in specific: the Voltage Source Inverter (VSI). This one is the most used topology to improve Active Power Filters (APFs) and Adjust Speed Drives (ASDs). Besides, nonlinear loads are composed by half or full-bridge rectifiers with or without a PWM control; DC/DC converters like Boost or Buck converters are widely used for charging domestic and mobile devices; so, from the Power Quality (PQ) framework, all of these devices are the cause of PQ problems such as flickering, harmonics, unbalances, low power factors, etc., and at the same time, PE are the solution to these problems; we have this kind of devices on both sides, from the load side and from compensators or power source side.

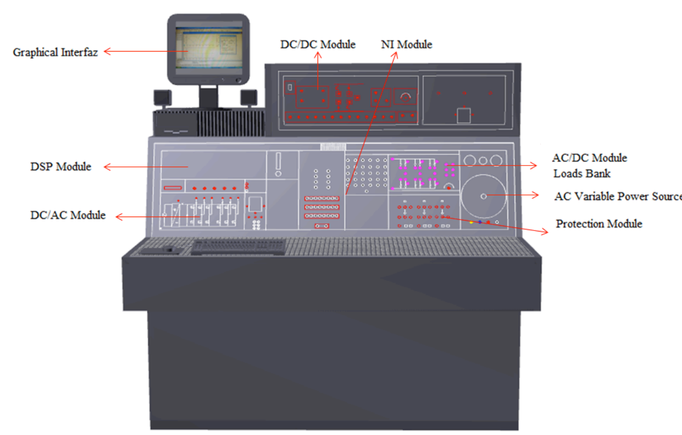
For research and educational purposes in power quality, probe control strategies are necessary for harmonic compensation and other problems, testing and corroborating new hypotheses and theories; to do that, easy prototypes are a reliable tool for rapid implementations and to make changes in the topology and configuration of the drive, testing new algorithms and make changes in the nature of the load safely and sequentially, change the power source level, etc.

In this paper we present two design and implementation methodologies for one of four workstations for the power electronics and power quality laboratory (LACEP) at Universidad Nacional de Colombia, Manizales campus. We focus in the one dedicated to the DC/AC-AC/DC conversion process, which has been designed for developing Rapid Control Prototypes (RCPs) and hybrid simulations for control APFs, and other power electronic devices like six-pulse totally controlled full-bridge rectifiers, ASDs, etc.; in addition, we present the original results of our work made with this workstation.

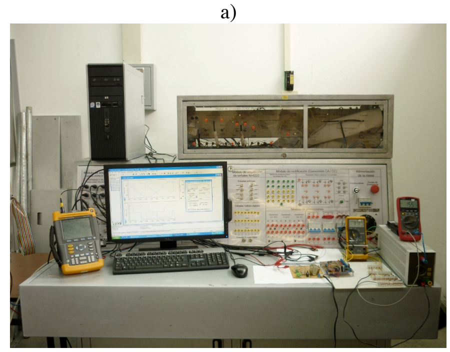
This paper will present in next SICEL 2013

II. A POWER WORKSTATION

The workstation is composed by eight main elements, all of them functioning together to convert electrical energy from DC to AC and vice versa.



a)



b)

Fig.1 A Power Workstation from LACEP at Universidad Nacional de Colombia, Manizales campus, a) design, b) implementation

The components are:

- Power inverter board
- Six-pulse full-bridge rectifier board
- DSP system and signal acquisition board
- Protection module
- AC power source module
- Turn-On/Off module
- Load module

All power boards have been designed for low voltage and low current applications in order to ensure safe working conditions in the laboratory. A brief description of each one of these modules but the power source and the on/off module are provided in the following.

A. Power Inverter Board

This is a three-phase full-bridge inverter with an active discharge topology, controlled by an IM 2133 microprocessor. With this board we can control two electric machines at the same time or configuring one of the two inverters as an APF [1, 2], or to improve a speed control for a DC machine [7].

The board has total compatibility with dSpace, which is a Digital Signal Processing system (DSP) with an easy to use graphical interface called Controldesk for visualizing all signals of interest via acquisition module [13], this module will be depicted in *Section II C*.

Fig. 2 Three Phase Power Inverter Board.

Figure 2 shows a board with three-phase full-bridge inverters, signal acquisition ports, communication port, heat sinks for power MOSFETS and capacitors for DC Link. The board in the figure is a design of Professor Ned Mohan at University of Minnesota [12]. We use this board as a three-phase power inverter source.

B. Full-Bridge Six Pulse Rectifier Module

In order to provide the opposite conversion process, the design of this module made possible the analysis of harmonic distortion generated by AC/DC converters under different load conditions [4]. We have two different full-bridge rectifiers, an uncontrolled six-pulse full-bridge rectifier and a totally controlled six-pulse full-bridge rectifier, the former made with power diodes and the latter made with power MOSFETs. We use a typical PWM control to commute these power switches.

The power circuit for the controlled rectifier is shown in Figure 3 and a control circuit for the rectifier is shown in Figure 4.

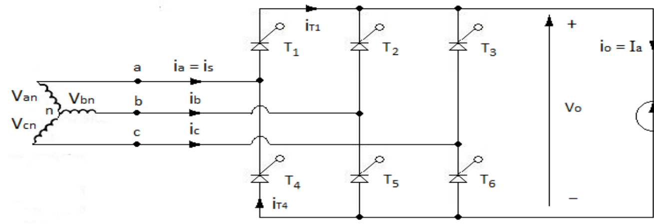


Fig. 3 Power Circuit for totally controlled six-pulse full-bridge Rectifier.

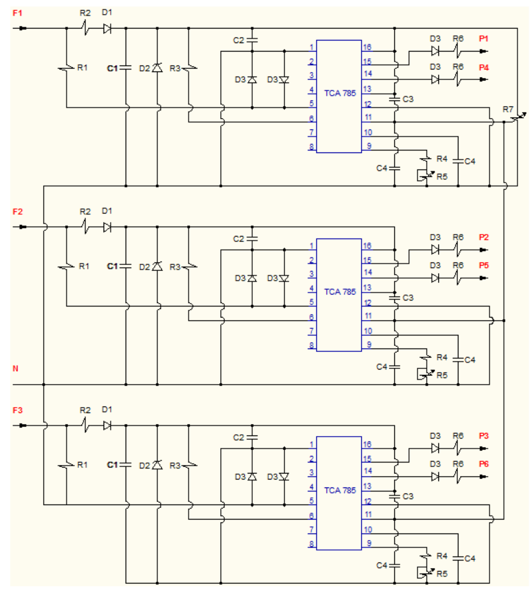


Fig. 4 PWM Control Circuit for totally controlled six-pulse full-bridge rectifier

The control circuit uses a PWM pattern to generate the switching sequence for turning on and off the MOSFET transistors, via gate signals. The integrated circuit used in this case was the TCA 785 [4].

The basic nonlinear load to probe a shunt active power filter is an uncontrolled full-bridge rectifier. We consider two types of rectifiers for testing active power filters.

C. DSP System and signal acquisition module

This module was designed minding the special need for visualizing a fair number of electrical signals, so we picked a 32 fully digital channels separated in two groups: 16 Analog to Digital (A/D) channels and 16 Digital to Analog (D/A) channels via a dSpace expansion board, plus two National Instruments electronic acquisition boards specially designed for acquiring electrical signals.

We also count with an easy graphical interface called ControlDesk [13] for visualizing all signals, similarly to how they are displayed in an oscilloscope. The control algorithms for all applications are coded using Matlab – Simulink [5, 6], real-time blocks (A/D, D/A channel blocks and three or four channel PWM control blocks). A screenshot of ControlDesk interface for a three-phase application is shown in Figure 5.

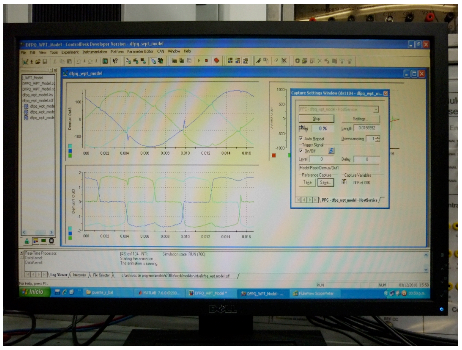


Fig. 5 Graphical Interface in ControlDesk for a three-phase application.

The input and output signals require a good electromagnetic environment to avoid the presence of common mode noise and thus prevent false or misleading switching sequences, i.e. we need to reconstruct and filter the current signals for nonlinear loads without any type of noise using Schmitt Triggers and other special integrated circuits. So, we hope that with the measuring circuits built for current and voltage sensing is possible to acquire the signals of interest and then process these waveforms properly.

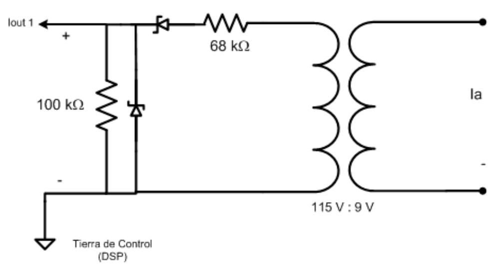


Fig. 6 Measurement circuit for voltage signals.

For this purpose we built two measurement circuits, one for voltage waveforms using a transformer with right transformation ratio and another for current waveforms using ACS714LLC-30A Hall effect transducers manufactured by Allegro, which generates a voltage proportional to the measured current from -30A to 30A. Figure 6 and 7 show these two measurement circuits, respectively.

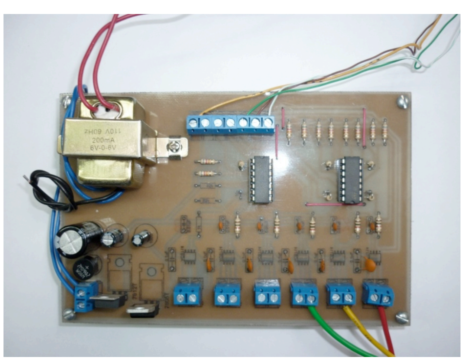


Fig. 7 Measurement circuit for current signals.

D. Electrical protection module

For safe experimentation we need to improve a protection module using different types of electrical devices like electromagnetic AC and DC breakers and relays. Table I summarizes the main values and devices for protection module.

TABLE I. TYPE OF PROTECTION DEVICES FOR PROTECTION MODULE

Element	**Value**
Tripolar Motor Breakers	20A
DC Breakers	30A
Tripolar AC Breaker 1	10A
Tripolar AC Breaker 2	20A
Tripolar AC Breaker 3	50A

E. Load module

A load bank is essential for making electrical experiments. With this module we can change from pure resistive load to inductive-capacitive (RLC) load in the DC side for full-bridge rectifiers. Resistors are variable and we can use three-phase induction motors as inductive load for an inverter system using it as ASD configuration, etc. A special set of 50W motors is included as a part of the load module. We can also use all rectifier modules like nonlinear loads for active power filters.

III. RAPID CONTROL PROTOPYPES AND HYBRID SIMULATIONS

Once all workstation modules are ready to use, it is necessary to apply some techniques for easy real-time experiments. In other words, we need to develop control algorithms for a specific device or for a set of them, and then compensate for some power quality perturbation, i.e. harmonics, flickering or unbalance. Fortunately, with DSP systems it is possible to implement two powerful tools for power quality and power electronics applications: one is rapid control prototyping and the other is hybrid simulation. Besides, we show a Shunt Active Power Filter (SAPF) made with a power inverter module, load bank module, DSP system and signal acquisition module (see *Sections IIA* to *IIE*). A SAPF is composed of five distinct elements (see the Figure 8):

a) PWM converter (power inverter module).

b) Current link between the inverter and the network connection point.

c) SAPF energy storage element (power inverter module).

d) Signal conditioning elements (DSP System and signal acquisition module).

e) A SAPF controller (DSP system and real-time Simulink model).

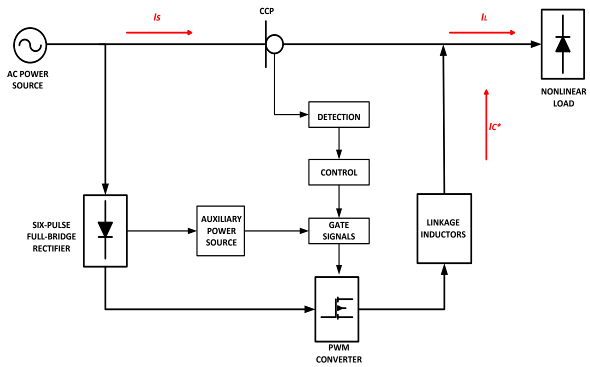


Fig. 8 Constitutive elements of a shunt active power filter.

One of our objectives is to implement a RCP for a SAPF using p-q Theory [1, 6], and then implement a hybrid simulation for a SAPF using the general power tensor (GPT) Theory [3, 5], both implementations are described in next sections:

A. Rapid Control Prototypes

A RCP consists of two main components: control algorithms and measurement circuits. The SAPF algorithm records phase currents and line voltages of a nonlinear load (in this case, an uncontrolled six-pulse full-bridge rectifier) in real-time. For this purpose, we employ the two measurement circuits illustrated in *Section IIC*.

In the experimental prototype we used the signal acquisition module and its measurement circuits for acquiring the electrical variables necessary for the SAPF control algorithm. Blue and red arrow/blocks from left to right in Figure 9 are voltage and current signals from a common connection point, the green block is a power calculation based on p-q Theory [9, 11], black arrows and the black block contain the six-pulse signals with commutation strategy for the Voltage Source Inverter (VSI) acting as SAPF (grey block), finally the dark blue block to the right hand side represents a nonlinear load, this could be the full-bridge rectifier described in *Section IIB*, remaining elements are part of the assembly for other research projects carried out at the laboratory.

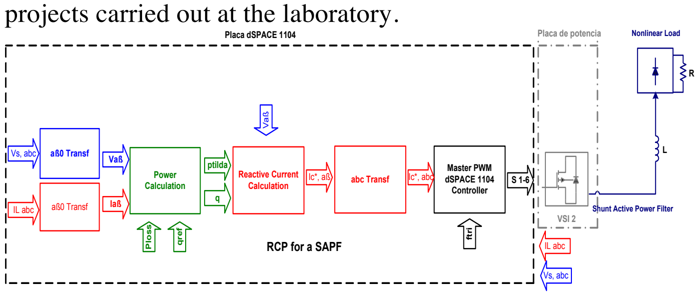


Fig. 9 Block Scheme for a rapid control protoype for the SAPF.

1) Constant source instantaneous power strategy

Instantaneous active current components are employed to develop the SAPF control algorithm. Active and imaginary powers (*p* and *q)* are calculated using [1].

Theoretically, this kind of compensation can be performed without energy storage elements. Normally, SAPFs are designed to compensate for oscillating real power ($\tilde{p}$), this is, the component of harmonic power present in the system due to the presence of nonlinear load. For the purpose of compensation, capacitors or inductors are required.

B. Hybrid Simulation

This type of simulation also known as hardware-in-the-loop simulation is a technique for combining physical and virtual components. Models consisting of two parts actively interacting are created during the simulation, (a) a physical subsystem - an experimental component representing a portion of a system and (b) a virtual subsystem - a computer model of the remainder of the system [2].

Control strategy generation in APF's using GPT theory is fully explained in [5].

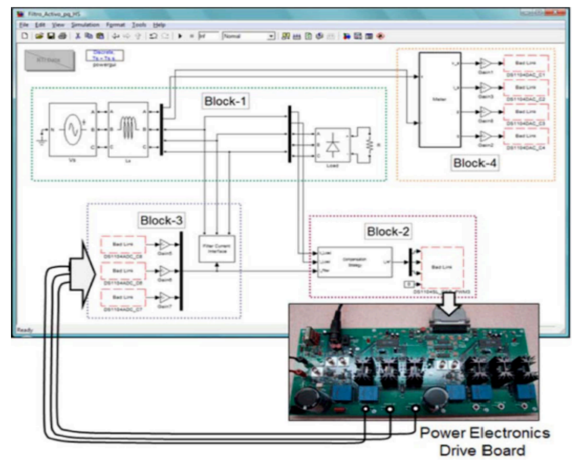


Fig. 10 Block Schematic for Hybrid Simulation.

Figure 10 shows the hybrid simulation algorithm scheme, various groups are highlighted in boxes in order to clearly differentiate them:

- Block 1 is composed by the power source and nonlinear load system in the real-time simulation, the three-phase source, the measurement circuits from load side and source side; the nonlinear load consisting of a full-bridge diode rectifier and a resistor at the DC side.
- Block 2 is part of the ControlDesk package integrated with Matlab. It is responsible for generating the PWM pulses to control the external inverter. The block also contains the control algorithm for calculating reference currents and on-off control.
- Block 3 fits dSPACE analogue inputs of the board, which are responsible for acquiring the current signal generated by the power inverter to be injected back to the simulated source-load system.
- Block 4 contains analog inputs; these are an integral part of the signal dSPACE acquisition board. They are used for measuring current, voltage and power in the prototype system.

IV. EXPERIMENTAL RESULTS

In this section we present the results of three experiments that have been made with the workstation previously described. The first one models a fully-controlled six-pulse rectifier for harmonic content analysis [4]; The second one implements a RCP for a shunt active power filter using p-q Theory [6] and performs a control strategy under constant power source constraint; the third one implements a SAPF based on GPT Theory [5] to improve a new control algorithm and to compare it against some other algorithms used for control these type of APF. In the next sections we show some results of these experiments.

A. *Totally Controlled Six Pulse Full-Bridge Rectifier*

The objective of this experiment is the design, simulation and implementation of the rectifier, with an analysis of harmonic distortion generated by the converter AC/DC under a resistive load. We are interested to see its influence in power quality, by implementing a reference to feed the control circuit (PWM), which generates common-mode noise [6].

For the test performed, we set the parameters illustrated in Table II.

TABLE II. ELEMENTS AND VALUES TOTALLY CONTROLLED SIX-PULSE FULL-BRIDGE RECTIFIER

Element	**Value**
Vab = Vbc = Vac	215 V
Ra = Rb = Rc	17 Ω
Rload	50 W
Power Inverter DC Bus	33 Ω
α	130°

The voltage waveforms in Figure 11 were obtained at the common connection point between the grid and the three-phase full-bridge rectifier. The equipment used for the acquisition of these signals is the Tektronix TDS 2014 oscilloscope. For current signals and current harmonic spectra, a Fluke scope-meter was used. Currents and spectra are also shown in Figure 11.

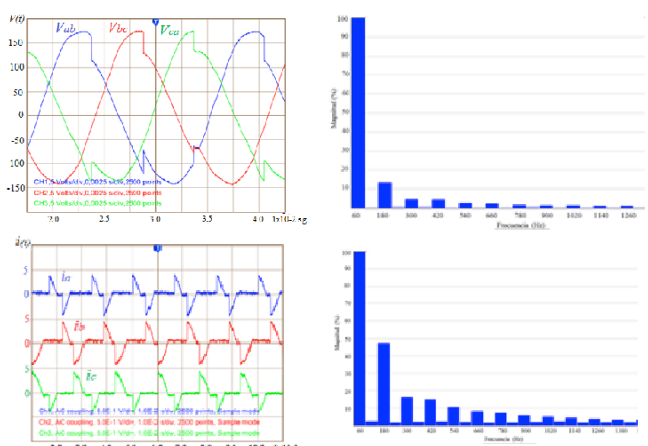


Fig. 11. Voltage, current waveforms and harmonic spectra for the totally controlled full–bridge rectifier.

B. *RCP for Shunt Active Power Filter*

We utilized the RCP for the SAPF (described in *Section III*). We measured and compared total harmonic distortion for current (THDi) and Power Factor (PF) parameters [14-18], as well as system current waveforms before and after compensation. We conducted a set of five experiments to test the control algorithm considering load variations (from pure resistive to RLC in the full-bridge rectifier DC side). The elements and values of the resistive-inductive load (RL) experiment are summarized in Table III.

TABLE III. ELEMENTS AND VALUES FOR THE RL EXPERIMENT

Element	**Value**
Load variable resistor	100 Ω
Load inductor	42,5 mH
Power Inverter Board	50 W
Power Inverter DC Bus	42 VDC
DC Link Capacitor	10000 uF
f_{PWM}	10 kHz

Nonlinear current signal for the A-phase is shown in Figure 12; the ridges on both half cycles in the signal differ when compared to a simulated signal. Ridges are asymmetrical and less pronounced in the real nonlinear load current waveform.

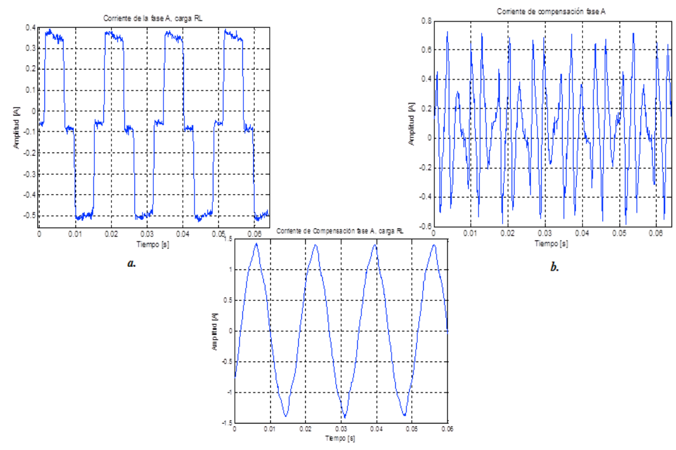


Fig. 12 A-Phase currents for the SAPF. a. Nonlinear load, b. compensation current and c. Current after compensation

The frequency spectrum has a similar range of harmonics: these are summarized in Table IV. The THDi is 20.94%. By comparing the experimental nonlinear current signal to current regulations [1], one can see that signal exceed recommended maximum values for individual and total distortion percentages.

TABLE IV. INDIVIDUAL HARMONIC DISTORTION FOR NONLINEAR LOAD CURRENT SIGNAL BEFORE COMPENSATION

Before compensation		
Harmonic	**Frecuency**	**% of Distortion**
1	60	-
3	180	2,4
5	300	18,7
7	420	9,7
9	540	1,4
11	660	4,7
13	780	2,5

When we compare the individual harmonic distortion from Table IV, with the results after applying compensation strategy in Table V, we see that every harmonic component is compensated. There is an oscillation in the implemented system due to common mode noise, which can be observed in the presence of the third harmonic after applying compensation, since current compensation is not flawless in any of the conducted experiments [6].

TABLE V. HARMONIC DISTORTION FOR NONLINEAR LOAD CURRENT SIGNAL AFTER COMPENSATION

After compensation		
Harmonic	**Frecuency**	**% of Distortion**
1	60	-
3	180	9,8
5	300	2,3
7	420	1,5
9	540	1
11	660	0,3
13	780	0,1

All in all, power quality three-phase parameters summarized in Table VI demonstrate that percentage of distortion is halved, however this is not enough to make the system reaching recommended values.

TABLE VI. POWER QUALITY INDEXES BEFORE AND AFTER COMPENSATION

Experiment	Before compensation	
Uncontrolled six pulse full bridge rectifier with RL load at DC side	**THDi (3ϕ) (%)**	**FP (3ϕ) (pu)**
	20,94	0,83
	After compensation	
	THDi (3ϕ) (%)	**FP (3ϕ) (pu)**
	10,63	0,93

C. Hybrid Simulation for Shunt Active Power Filter Based on Instantaneous Power Tensor Theory

This section presents the proposed hybrid simulation applied in the APFs design stage [5]. Here, a source-load system was simulated (MATLAB-Simulink-ControlDesk) while the inverter system was implemented as external hardware (dSPACE-Inverter). The experimental results captured with the Fluke oscilloscope and ControlDesk interface are shown in Figure 13. The figure shows the A-phase waveforms and spectrum on the source side for the experimental hybrid prototype implemented. Figure 13(a) shows voltage waveform and spectrum. Figure 13(b) shows results for the system without compensation where high harmonic content generated by the nonlinear load was noticed. Figure 13(c) shows current waveform harmonic content decreased after compensation with the RPT (Real Power Tensor) strategy, although not being satisfactory. This is because the compensation strategy sought to reduce reactive and non-cancelling harmonics. Figure 13(d) shows that the NPC (Non Power Conformity) strategy was the most responsive in terms of individual and total harmonic distortion current.

The results of harmonic and current harmonic distortion for each compensation strategy are summarized in Table VII, Here, it can be clearly seen that the current signal is corrected for each strategy and a quasi-sinusoidal wave substitutes the original waveform when the filter is connected.

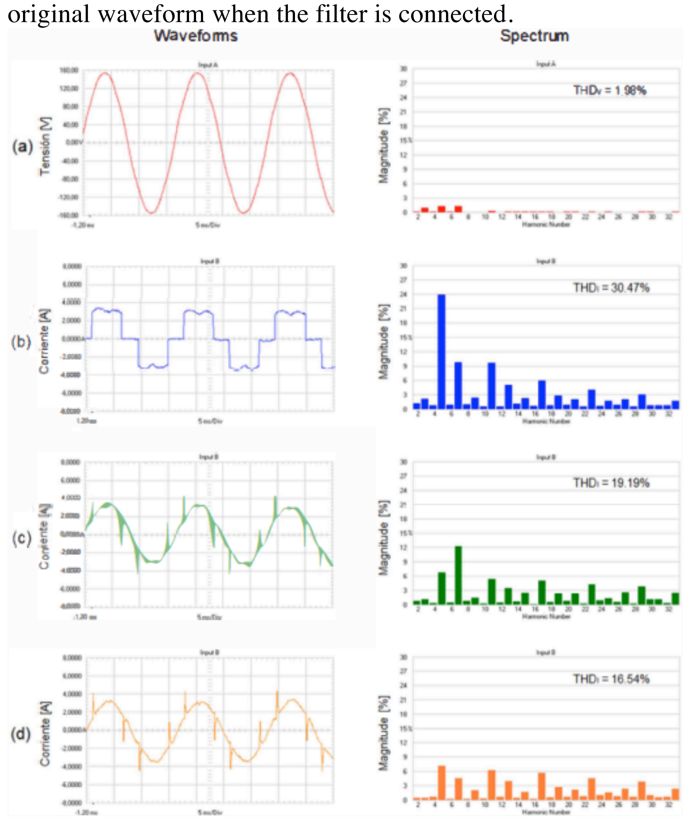


Fig. 13 Waveforms and spectrum in the source side -hybrid simulation results: a) voltages, b) without APF, c) RPT and d) NPC.

The small ripple in the signal is due to the strategy of modulation and not to the calculation of the reference current. In addition, from the results shown in Table VII, as expected, the hybrid simulations is closer to the true behavior of the inverter bridge than that the one based on the conventional simulation.

TABLE VII. SUMMARY OF HARMONIC AND CURRENT HARMONIC DISTORTION

Strategies	Harmonic [%]				THDi[%]
	5th	7th	11th	13th	
Conventional simulation results					
No Compensation	24.6	9.9	10.1	5.1	33.3
RPT	3.8	7.4	1.3	1.3	12.2
NPC	1.2	1	1.3	0. 8	8.6
Hybrid simulation results					
No Compensation	24	9.8	9.7	5.1	30.5
RPT	6.7	12	5.3	3.4	19.2
NPC	7.2	4.5	6.3	3.9	16.5

V. CONCLUSIONS

- The presented workstation can be used to develop APFs, nonlinear loads like full-bridge uncontrolled/controlled rectifiers, and to corroborate existing and new theories on electric power to compare their benefits in power quality.

- The RCPs and the hybrid simulation techniques proved to be suitable to develop our researches, we can make changes on experiments in an easy way and we can demonstrate the control strategies to switch power electronics converters and resolve power quality problems.

- The workstation allows full control over the entire energy conversion process; also, it is easy to perform signal post-processing in the frequency domain and in the power tensor domain for more detailed analysis.

- Further research is now possible with this workstation looking for original and novel results, we can search how to decrement the electromagnetic interference between power inverter module, rectifier modules and DSP system module, extend this design to other workstations at power quality laboratory and so complete our installations.

ACKNOWLEDGMENTS

Thanks to Distribution and Power Networks Group –GREDyP–, Department of Electrical Engineering and Computer Science –DIEEC– at the Universidad Nacional de Colombia for all the support, confidence and resources provided, to the co-authors for all your patience during difficult times; finally to Ph.D. Ricardo Henao G. for his contributions to the definitive English version of this paper.

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