Hybrid simulation: an active power filter case study

Simulación híbrida: caso de estudio en un filtro activo de potencia

Y.A. Garcés[1], E.A. Cano-Plata[2], A.J. Ustariz-Farfan[3]

***Abstract*— The hybrid simulation concept consisting of a combination of computer simulation and laboratory tests. This approach is a cost effective alternative to physically testing the whole system and allows better understanding of complex coupled systems. This paper describes implementing an active power filter (APF) hybrid prototype where the source system and load are implemented as a real-time simulation and the system of static power converter acting as an active power filter is implemented in physical hardware. It also confirmed the hybrid simulation results by implementing the simulation in MATLAB-Simulink regarding the same system implemented during the active power filter analysis and design stage.**

***Index terms:* active power filter, hybrid simulation, power inverter.**

***Resumen*— El concepto de simulación hibrida consiste en la combinación de simulaciones por computador y pruebas de laboratorio físicas. Este enfoque es una alternativa rentable a las pruebas físicas de todo un sistema, y permite la mejor comprensión de los complejos sistemas acoplados. Este artículo describe la implementación de un prototipo híbrido de filtro activo de potencia (APF), donde se implementa el sistema de fuente y la carga en simulación en tiempo real, y el sistema de convertidor de energía estática que actúa como filtro activo de potencia se implementa en hardware. Además, se confirman los resultados de simulación híbrida con la implementación de la simulación numérica en MATLAB-Simulink del mismo sistema implementado en la etapa de análisis y diseño del filtro activo de potencia.**

***Palabras Clave:* filtro activo de potencia, simulación hibrida, inversor de potencia.**

[1] Specialist, Electronic Engineering, Universidad Nacional de Colombia, M.Sc. in Engineering, Universidad Nacional de Colombia, Ph.D. Student in the Department of Electrical, Electronics and Computer Engineering, Universidad Nacional de Colombia, Manizales Branch, Manizales-Colombia (e-mail: yagarsesg@unal.edu.co)

[2] Specialist, Electrical Engineering, Universidad Nacional de Colombia, Ph.D. in Engineering, Universidad de Buenos Aires, Argentina, Titular Professor with the Department of Electrical, Electronics and Computer Engineering, Universidad Nacional de Colombia, Manizales Branch, Manizales-Colombia (e-mail: ecano@ieee.org)

[3] M.Sc., Electrical Engineer, Universidad Industrial de Santander, Ph.D. in Engineering, Universidad Nacional de Colombia, Colombia. Associate Professor with the Department of Electrical, Electronic and Computer Engineering, Universidad Nacional de Colombia, Manizales Branch, Manizales–Colombia, (e-mail: ajustarizf@unal.edu.co)

1. INTRODUCTION

Traditionally, numerical simulation and physical tests have been performed separately and their results then validated. Hybrid simulation is a multidisciplinary technology which is heavily based on mechanical and computational dynamics, control theory, computer science and numerical methods. It currently has applications in the aerospace industry and civil, mechanical and automotive engineering (Saouma and Sivaselvan, 2008).

A search of the literature using the term “hybrid simulation” revealed that this has been in use for quite some time in various areas of knowledge, such as computer science (Donzelli and Lazeolla), animation and computer graphics (García, 2004; Sifakis et al, 2007), robotics, control theory (Álvarez et al, 2009), bioinformatics, chemistry (Kalstein et al), materials engineering (Foit, 2010) and civil engineering Chen and Ricles, 2009; Kausel, 1998a; Kausel, 1998b; Muñiz et al, 2002), where the common element in all applications appears to lie in the combination, coordination and synchronisation of discrete event simulations on a computer with external processes regarding continuous analogue signals.

In the area of logistics information systems in the data processing technologies category, hybrid simulation is defined as an approach combining different types of simulations, typically in a distributed environment, usually involving combined, simulators with real operational equipment, prototypes of future systems and realistic representations of operational environments. The McGraw-Hill Science & Technology Dictionary defines the term as the use of hybrid computer simulation, understanding a hybrid computer as that computer designed to handle both analogue and digital data.

This paper is organized as follows. Section 2 describes the definition of active power filter. Section 3, presents the proposed hybrid simulation applied in the APFs design stage. In Section 4 practical applications of the hybrid simulation are presented. Finally, in Section 5 the most important conclusions are presented.

2. ACTIVE POWER FILTER

It is very important for power generation companies to prevent current harmonics (which create electromagnetic interference and resonance problems) and to limit the flow of reactants (which generate transmission loss). Traditionally, passive filters, consisting of tuned LC elements and capacitor banks, were used to filter the harmonics and compensate reactive power generated by nonlinear loads. However, such methods have many disadvantages in practical applications.

There has been considerable progress in the field of APF during the last two decades, with different topologies and control techniques having been proposed for its implementation. APFs are superior to passive filters in terms of filtering capacity and improve system stability by removing the problems related to resonance capacitor banks.

APFs are static power converters controlling the generation of currents or voltages to compensate for undesirable power system components; the best known and applied topologies are currently (Fuchs and Masoum, 2008):

- Single phase active filters.
- Three-phase three-wire active filters.
- Three-phase four-wire active filters.

Also, according to their capacity, they can also be grouped as follows:

- *Low-power active filters*: having less than 100kVA power range and 10µs and 10ms response times. They are mainly used in residential areas, small and medium industries, commercial buildings and hospitals. These applications require sophisticated dynamic filtering techniques, and include single and three phase systems.
- *Medium-power active filters*: having 100kVA to 10MVA power ratings and 100ms to 1s response times. They are mainly associated with medium- to high-voltage distribution systems and high-power, high-voltage drive systems where the effect of phase imbalance is negligible. Due to economic concerns and problems associated with high-voltage systems (isolation, series or parallel connections of switches, etc.), these filters are usually designed to perform harmonic cancellation, and reactive-power compensation is not included in their control algorithms.
- *High-power active filters*: having power ratings above 10MVA and response times in tens of seconds, are mainly associated with power transmission grids, ultrahigh- power DC drives, and HVDC.

APFs can be combined with passive filters to form a variety of topologies called hybrid power filters.

A. *Controlling active power filters*

Filter configuration is the initial state of any active filtering, depending on the nature of the distortion to be dealt with, the system's structure and the required accuracy and compensation speed. Possible responses that may require compensation are:

- *Harmonic distortion*: is the change in the waveform of the supply voltage from the ideal sinusoidal waveform. Besides, is listed as APFs' primary function.
- *Active and reactive instantaneous power*: concerning all the portions of power in the phases that do not contribute to instantaneous active power flow between the source and load.
- *Components from negative and zero sequence:* which refer to the imbalance and neutral current in the electrical networks.
- *Flicker*: is an irregular low frequency modulation that presented in the voltage source.
- *Voltage sags and swells*: are short-duration decreases or increases in steady-state voltage, generally caused by the connection of significant loads or capacitor banks over-compensating the system.

B. *Shunt active power filter*

Figure 1 shows the basic layout of a shunt active filter with injection current control, taking the sample current and load voltage and generating the reference currents to be injected into the system and thus draw a sinusoidal current deep at source.

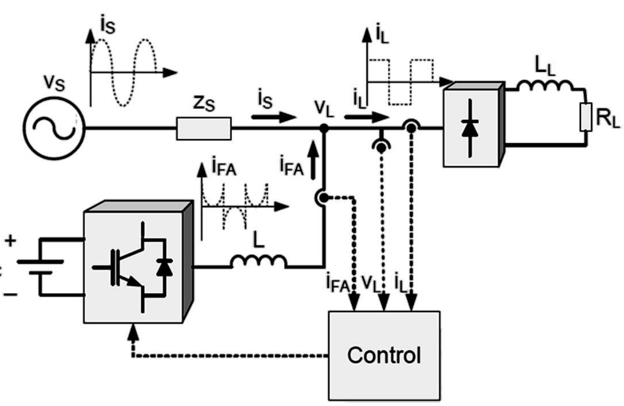

Figure 1: Basic diagram of a shunt active power filter

Figure 1 shows the main APF system components described as follows:

- *Transducers:* are used in various parts of the system; initially, current and voltage are measured at the load side to be admitted to the control block (v_L e i_L) and generates the reference currents (i_F). The injected current compensation system is also measured for the inverter to close the control loop. Voltage and current can be measured using Hall effect transducers.
- *Power inverter*: is a controlled static power converter with a corresponding coupling inductance which is responsible for reproducing the waveform with proper amplitude for filtration;
- *Inverter control*: is usually configured as pulse width modulator (PWM) with a local control loop current to ensure that the current generated by the filter with an acceptable error is the reference current generated by measuring load current and voltage; and

- *DC bus*: consisting of an energy storage element which provides the instantaneous power demanded by the power inverter.

3. HYBRID SIMULATION: APFS DESIGN APPLICATION

This section presents the proposed hybrid simulation applied in the APFs design stage (Garcés, 2011). Here, a source−load system was simulated (MATLAB-Simulink-ControlDesk) while the inverter system was implemented in external hardware (dSPACE-Inverter).

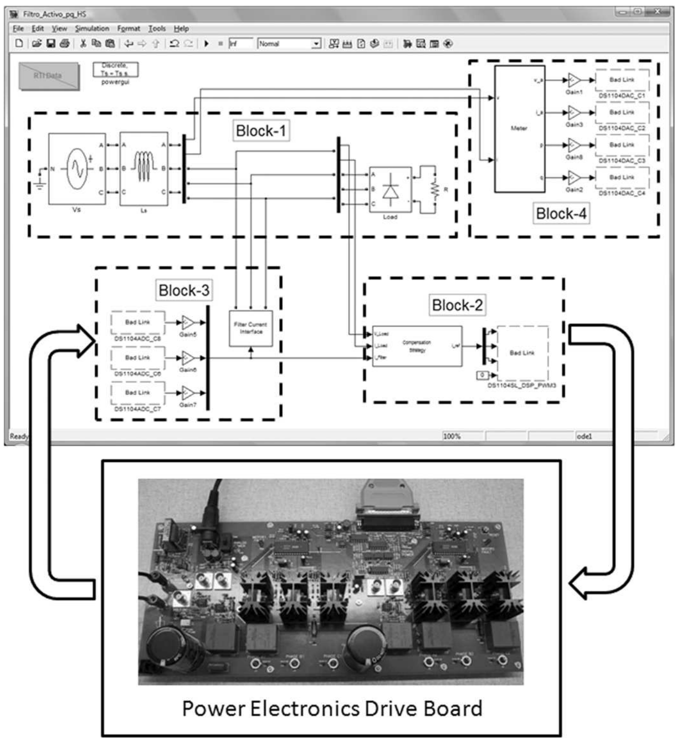

Figure 2: Hybrid simulation algorithm scheme

The hybrid simulation allows developers to accurately and efficiently simulate electrical power systems and their ideas to improve them. The hybrid simulation operates in real time, therefore not only allowing the simulation of the power system, but also making it possible to test physical equipment (an APF based VSI bridge, in this case). This gives developers the means to prove their control strategy, prototypes and final products in a realistic environment.

Figure 2 shows the hybrid simulation algorithm scheme. Here, various groups are highlighted in boxes in order to clearly describe that:

- *Block-1:* This group in the algorithm was the source−load system in real-time simulation, recognising the three phase source, the measurement items load side and source side, the nonlinear load consisting of a three phase diode bridge and a resistor.
- *Block-2:* This group was part of the ControlDesk software package integrated with Matlab. This block was responsible for generating the PWM pulses to control the external inverter. This block also contained the control algorithm for calculating the reference currents and the on-off control.
- *Block-3:* The dSPACE control analogue inputs of the board were responsible for acquiring the current signal generated by the power inverter to be injected back to the simulated source−load system.
- *Block-4*: The dSPACE control board analogue outputs for external monitors the voltage, current and power variables.

4. COMPARISONS WITH THE CONVENTIONAL SIMULATION

To establish a connection with the conventional simulation, in this section, a three-phase ideal voltage source that feed a rectifier with resistive load at the DC side is compensated with an APF. For comparison proposes, done using both conventional and hybrid simulations under same source-load conditions.

In both cases, the estimate of the reference current for the control of the APF is given by the instantaneous-time or the average-time compensation strategies (instantaneous reactive power –IRP and perfect harmonic cancellation –PHC methods (Montero et al, 2007; Ustariz et al, 2010)).

A. Conventional simulation results

To better understand the meaning of hybrid simulation, initially the active filter is modelled as an ideal IGBT power inverter bridge. Figure 3 shows the implemented circuit in MATLAB-Simulink.

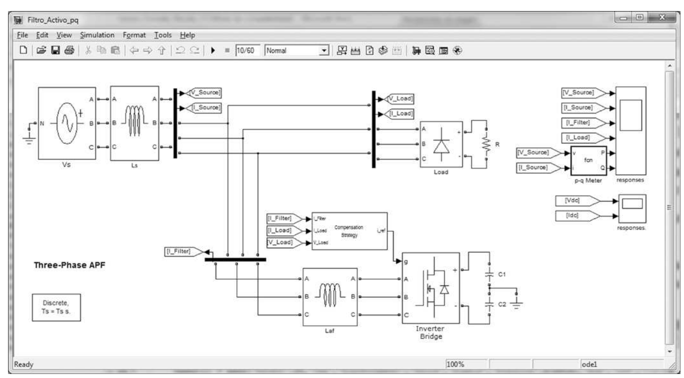

Figure 3: Conventional simulation algorithm scheme

Figure 4 displays the current waveforms and a-phase current spectrum on the source side for the simulated cases different. Here, the emphasized signal corresponds to the a-phase. Figure 4(a) shows the simulation results for the case where the APF is not connected. Figure 4(b) shows the simulation results for the case where the APF is controlled with the –IRP strategy. Figure 4(c) shows the simulation results for the case where the APF is controlled with the –HPC strategy. Here, small transients appear in the moments of switching the bridge inverter.

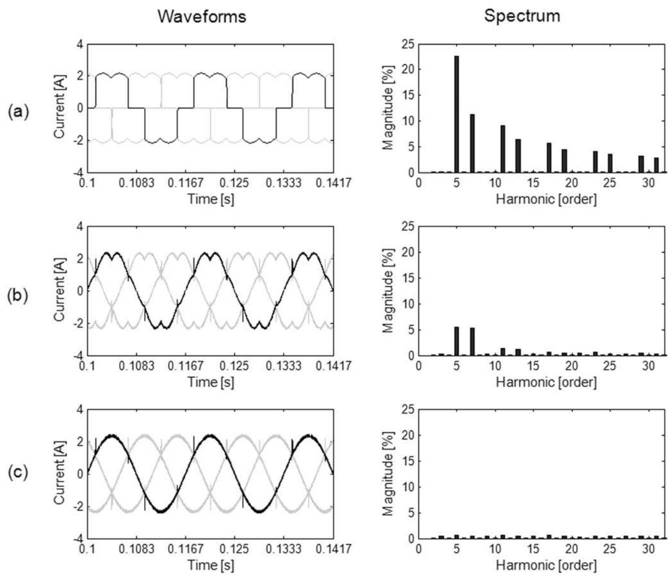

Figure 4: Current waveforms and spectrum in the source side -conventional simulation results: a) without APF, b) –IRP strategy and c) –PHC strategy

Figure 5 shows the instantaneous active and reactive power on the source side for the simulated cases different. Figure 5(a) shows the simulation results for the case where the APF is not connected. Figure 5(b) shows the simulation results for the case where the APF is controlled with the –IRP strategy. Figure 5(c) shows the simulation results for the case where the APF is controlled with the –HPC strategy.

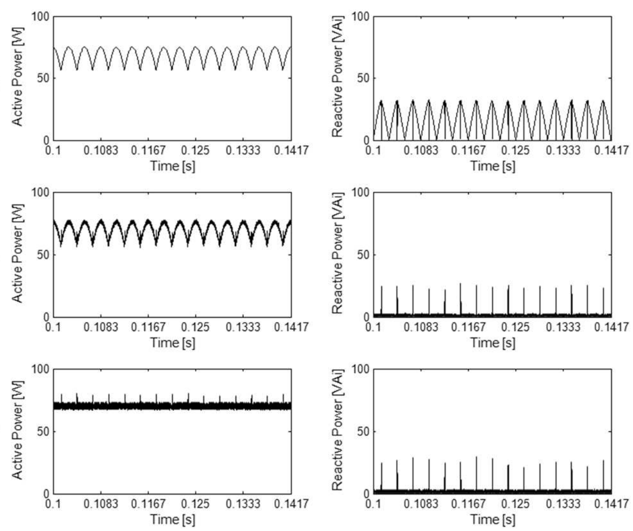

Figure 5: Instantaneous active and reactive power in the source side -conventional simulation results: a) without APF, b) –IRP strategy and c) –PHC strategy

B. Hybrid simulation results

Now, the same source-load-filter system shown above is implemented using the proposed hybrid simulation.

Figure 6 shows the real time control board management programme showing load and source currents on the left-hand side, the active and reactive power at the top centre, and compensation currents generated by both control algorithms such as that generated by the inverter in the central lower part, as well as on and off controls for APF operation.

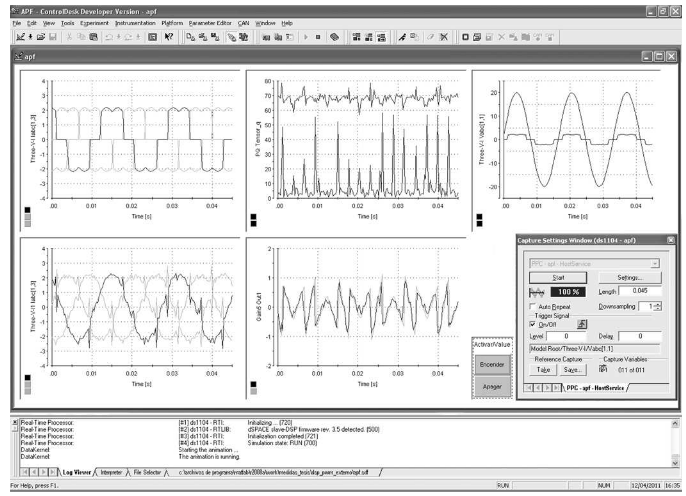

Figure 6: ControlDesk - hybrid simulation interface

The experimental results captured with the Fluke oscilloscope and ControlDesk interface are presented in Figures 7 and 8 respectively.

Figure 7 displays the a-phase current waveforms and spectrum on the source side for the experimental prototype hybrid implemented. Figure 7(a) shows the results for the system without compensation where high harmonic content generated by the nonlinear load was noted. Figure 7(b) shows that current waveform harmonic content decreased after compensation with the –IRP strategy, although not being satisfactory. This was because this compensation strategy sought to reduce reactive and non-cancelation harmonics. Figure 7(c) shows that the –HPC strategy was the most responsive in terms of individual and total harmonic distortion current.

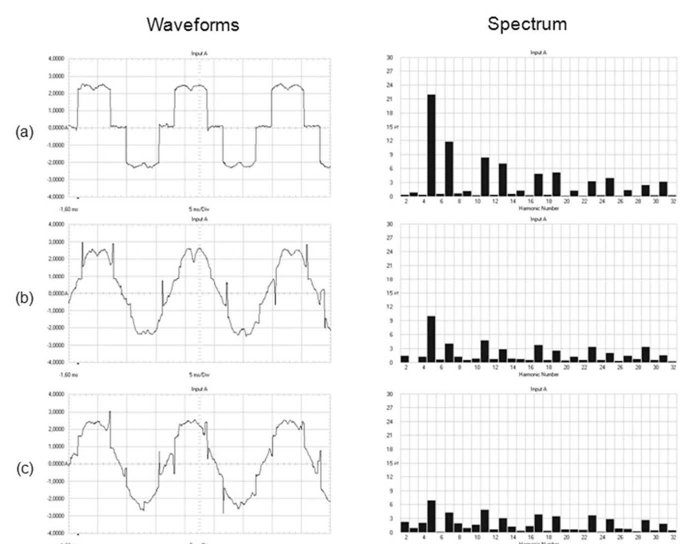

Figure 7: Current waveforms and spectrum in the source side -hybrid simulation results: a) without APF, b) –IRP strategy and c) –PHC strategy

Figure 8 shows the instantaneous active and reactive power on the source side for the experimental prototype hybrid implemented. Figure 8(a) shows the experimental results when the APF is not connected. Figure 8(b) shows the experimental results for the case where the APF is controlled with the –IRP strategy. Figure 8(c) shows the experimental results for the case where the APF is controlled with the –HPC strategy.

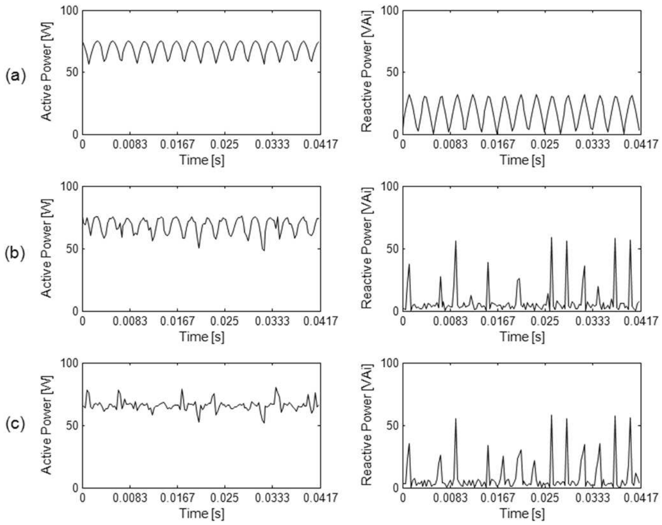

Figure 8: Instantaneous active and reactive power in the source side - hybrid simulation results: a) without APF, b) –IRP strategy and c) –PHC strategy

C. *Results analysis*

The results of harmonic and current harmonic distortion for each compensation strategy are summarized in Table 1.

Table 1: Summary of harmonic and current harmonic distortion

Strategies	Harmonic [%]				THDi [%]
	5^{th}	7^{th}	11^{th}	13^{th}	
Conventional simulation results					
No Compensation	22.63	11.30	9.03	6.44	30.25
ITC	5.44	5.28	1.26	1.03	8.54
PHC	0.46	0.56	0.51	0.49	4.43
Hybrid simulation results					
No Compensation	21.9	11.8	8.3	7.0	29.72
ITC	10.0	4.0	4.8	2.8	16.42
PHC	6.8	4.2	4.7	2.9	13.96

The results shown in Table 1 are based on conventional and hybrid simulations. Here, 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. The small ripple in the signal is due to the strategy of modulation and not due to the calculation of the current reference. Besides, from the results shown in Table 1, as expected, the hybrid simulations is closer to the true behavior of the inverter bridge than that the based one on the conventional simulation.

5. CONCLUSION

In this paper, an active power filter has been implemented with the hybrid simulation that has been suggested. The proposed tool is a first approach to the design of active power filters. The show results in this paper allow comparing the hybrid simulation with a fully simulated system in a computer.

This comparison showing that the hybrid simulation was a good option for dealing with hardware implementation issues in testing and laboratory prototypes.

6. ACKNOWLEDGMENTS

This work is supported by the Research Group on Distribution and Transmission Systems “GREDyP” from Universidad Nacional de Colombia, Sede Manizales, and its Power Electronics and Power Quality Laboratory “LACEP”, and the program Jóvenes Investigadores de COLCIENCIAS-Virginia Gutiérrez de Pineda.

7. REFERENCES

Álvarez G, C., Soto P, A., and Watkins O, F., “Simulación de controladores digitales,” Ingeniare. Revista chilena de ingeniería, vol. 17, no. 3, pp. 309–316, Diciembre 2009.

Chen, C. and Ricles, J. M. “Servo-hydraulic actuator control for realtime hybrid simulation,” American Control Conference, pp. 5222– 5227, 2009.

Donzelli, P. and Iazeolla, G. “Hybrid simulation modelling of the software process,” laboratory for Computer Science and CERTIA Research Center, University of Rome “TorVergata”.

Foit, K. “An introduction to the hybrid simulation, the conception of the simulation system,” Journal of Achievements in Materials and Manufacturing Engineering, vol. 39, no. 2, pp. 176–183, April 2010.

Fuchs, E.F., and Masoum, M. A. S., Power Quality in Power Systems and Electrical Machines. 30 Corporate Drive, Suite 400, Burlington, MA 01803, USA: Academic Press - Elsevier, 2008.

Garcés, Y. A. “Filtro activo de potencia controlado con la teoría del tensor instantáneo de potencia,” Master’s thesis, Universidad Nacional de Colombia, Sede Manizales, Mayo 2011.

García, I. G. “Simulación híbrida como núcleo de simulación de aplicaciones gráficas en tiempo real,” Ph.D. dissertation, Universitat de Valéncia, 2004.

Kalstein, A., Soler, M. A., Bastida, A. and Fernández-Alberti, S., “Simulación híbrida clasico-cuantica de la relajación vibracional del modo amida i de la n-metil acetamida (nma) en solución,” Universidad Nacional de Quilmes y Departamento de Química- Física, Facultad de Química, Universidad de Murcia.

Kausel, E., “New seismic testing method. i: Fundamental concepts,” Journal of Engineering Mechanics, vol. 124, no. 5, pp. 565–570, May 1998a, prof. of Civ. and Envir. Engrg., Massachusetts Inst. of Technol.

Kausel, E., “New seismic testing method. ii: Proof for mdof systems,” Journal of Engineering Mechanics, vol. 124, no. 5, pp. 571–575, May 1998b, prof. of Civ. and Envir. Engrg., Massachusetts Inst. of Technol.

Montero M.I.M., Cadaval E.R. and Gonzalez F.B., “Comparison of Control Strategies for Shunt Active Power Filters in Three-Phase Four-Wire Systems,” IEEE Trans. Power Electron., vol. 22 no 1, pp. 229–236, Jan. 2007.

Muñiz, J. A., Engel, R., Gaisser, T. K., Ortiz, J. A., and Stanev, T., “Hybrid simulations of extensive air showers,” Bartol Research Institute, University of Delaware, Newark, 2002.

Saouma, V., and Sivaselvan, M., Eds., Hybrid Simulation. Theory, Implementations and Applications. Taylor & Francis Group, 2008.

Sifakis, E., Shinar, T., Irving, G., and Fedkiw, R.,“Hybrid simulation of deformable solids,” Eurographics, ACM SIGGRAPH Symposium on Computer Animation, 2007.

Ustariz, A. J., Plata, E. C. and Tacca, H. E. “Tensor analysis of the instantaneous power in electrical networks,” Electric Power Systems Research, vol. 80, pp. 788–798, January 2010.