MULTI -FPGA SOLUTION FOR LARGE POWER SYSTEMS AND MICROGRIDS REAL TIME SIMULATION

TEJKIRAN RANGINEEDI, SYED QASEEM Ali, AMINE YAMANE, LUC-ANDRE GREGOIRE, JEAN-NICOLAS PAQUIN, JEAN BELANGER
OPAL-RT Technologies

SUMMARY

This paper presents a Multi FPGA based solution for large power systems and Microgrids real-time simulation. The proposed platform allows control and protection devices to be designed and tested in virtual power system, before they can be implemented in a physical system. This solution promotes flexibility of operation with no risk of components failure under any contingency analysis. To demonstrate the effectiveness of the OPAL-RT platform, a large distribution network (DN) of 210 bus bars and a Microgrid (MG) are considered. The MG includes a solar panel and a battery energy storage system (BESS). The complete power system including the DN and MG is simulated using only two Kintex-7 FPGA boards. The controllers of the MG distributed energy resources (DER) are compiled and real time simulated using a 3.5 GHz Intel processor. The performance of this overall Processor-In-The-Loop application (PIL) is validated based on two criteria: 1) Evaluation of the results accuracy compared to the reference offline simulation under steady state and transient conditions. 2) Evaluation of the numerical stability of the power interface used to split the DN into two FPGA boards.

KEYWORDS

Micro-grid, Distribution Network, Real time simulation, FPGA, PIL, PV, BESS

Amine.yamane@opal-rt.com

1. INTRODUCTION

With the increased complexity of modern power grids and the integration of renewable energy sources, industry is relying on simulation tools more than ever for the prototyping and design of power systems. In recent years, digital real-time simulators have become essential to the design of smart and micro grids, as well as for testing control and protection schemes [1]–[4].

However, modern distribution grids rely heavily on power electronics systems, which increase the complexity of power systems containing a large number of distributed generation sources. Hence, the real-time simulation of modern electrical networks faces two major challenges that need to be addressed by a real-time simulator:

1. The simulation of distribution networks comprising a large number of components, modules and bus bars;
2. The accurate handling of fast switching frequency power converters.

The remainder of this paper is organized as follows: Section II provides background material about real-time simulations, as well as the challenges associated with large power networks and fast switching frequency power converters. Section III discusses the case study considered in this paper. Section IV concludes this work.

2. KEY-CHALLENGES OF REAL-TIME SIMULATION

Power grids in general, are complex systems and their electromagnetic transient simulation requires the computation of large matrices. The only way for a real-time simulator to handle the simulation in real-time is to split the grid model over multiple computation units.

1.1 Real-time simulation of large distribution networks

Distribution networks are lumped by nature, and network decoupling using natural delays (transmission lines) is not always possible.

The simplest method to split the computation over multiple FPGA boards is the so-called Ideal Transformer decoupling Method (ITM) [5]. This method consists of using a parasitic load (snubber) at each decoupling location. The snubber parameters depend principally to the sample time of the real-time simulation. Since the simulation on the FPGA is performed with very low simulation time step (100 Nano-seconds to 5 Micro-seconds), the ITM method can provide a good compromise between the simulation accuracy and the numerical stability.

The decoupling method used in this paper is called distributed inductance power interface [11], also known as stubline. It consists of a lossless traveling line, which is the equivalent of an inductance with shunt parasitic capacitance [12].

1.2 Real-time simulation of fast switching frequency power electronic systems

FPGA-based real-time simulators have been proven to be the computing platform of choice for the simulation of power electronic systems [6], [7] because of the high switching frequencies (>10 kHz) targeted by most modern power conversion systems [8], [9]. To avoid the tedious FPGA design workflow, we use eHS, an automated FPGA-based computing engine [10], consisting of a pre-compiled hardware processor that converts a SimPowerSystems circuit into binary data used by eHS.

Amine.yamane@opal-rt.com

1.3   Hardware setup and FPGA boards coupling

Once the micro-grid model has been split between two FPGA boards, there is a need to couple and synchronize both decoupled circuits. The issue with this is the losses that will be introduced by the decoupling method. It is one of the contribution of this paper to evaluate the effectiveness of both: the ITM, and the distributed inductance decoupling methods when using the FPGA-Based real time simulation platform.

The hardware setup is given in figure 1. It consists of two FPGA Boards of type Kintex-7 connected together with a small form-factor pluggable (SFP) link. The synchronization is performed by considering the first FPGA board as the master sending the synchronization signals to the other slave FPGA boards.
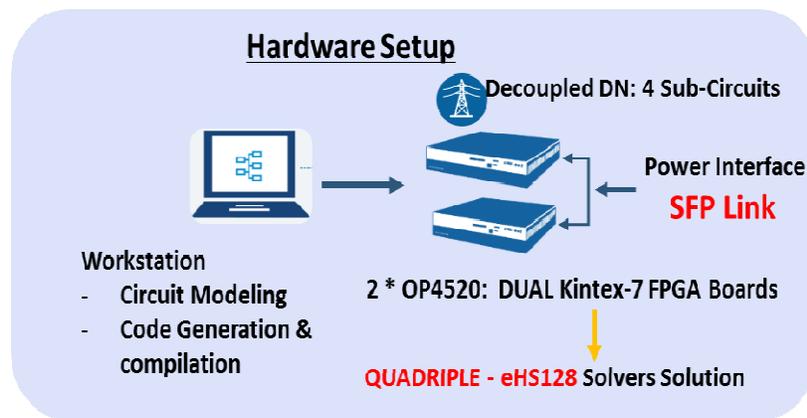

Figure 1: Multi-FPGA Platform hardware setup

3. Case study

The case study considered to demonstrate the effectiveness of the OPAL-RT FPGA-Based real time simulation platform, consists of a micro-grid connected to a large distribution network comprising 210 three-phase bus bars, as shown in Figures 6 and 7.

The complete 210 bus bars distribution network depicted in figure 6 including the MG given in figure 7 is simulated using only two Kintex-7 FPGA boards with a simulation sample time of 2.5 micro-seconds. Table 1 summarizes the DN contents as well as the FPGA Boards allocation.

3.1   Power Distribution system Real Time Simulation Validation
To validate the OPAL-RT Multi-FPGA Solution, several simulation tests were performed. The validation is done in terms of the accuracy of results and also the numerical stability of the platform. In terms of accuracy, the results of the real time platform are compared to the reference offline model developed using SimPowerSystems toolbox. To evaluate the numerical stability, several type of faults were performed at different locations in the system. Figure 2 shows a sample of results at bus bar 3 in case of a three-phase to ground fault compared to the reference results obtained using SimPowerSystems solver.

Amine.yamane@opal-rt.com

Table 1: Tested Power system and real time performance

NB.FPGA Boards	Model Content	Description	FPGA Time Step
DUAL OP4520 - Kintex-7	——	208 3-Ph RL connections	**FPGA 1:** 2.5 us .
	↓	124 3-Ph RL Loads	
	▌	210 3-Ph Bas Bars	**FPGA 2:** 2.5 us .
	⚡	5 3-Ph Breaker Circuits	
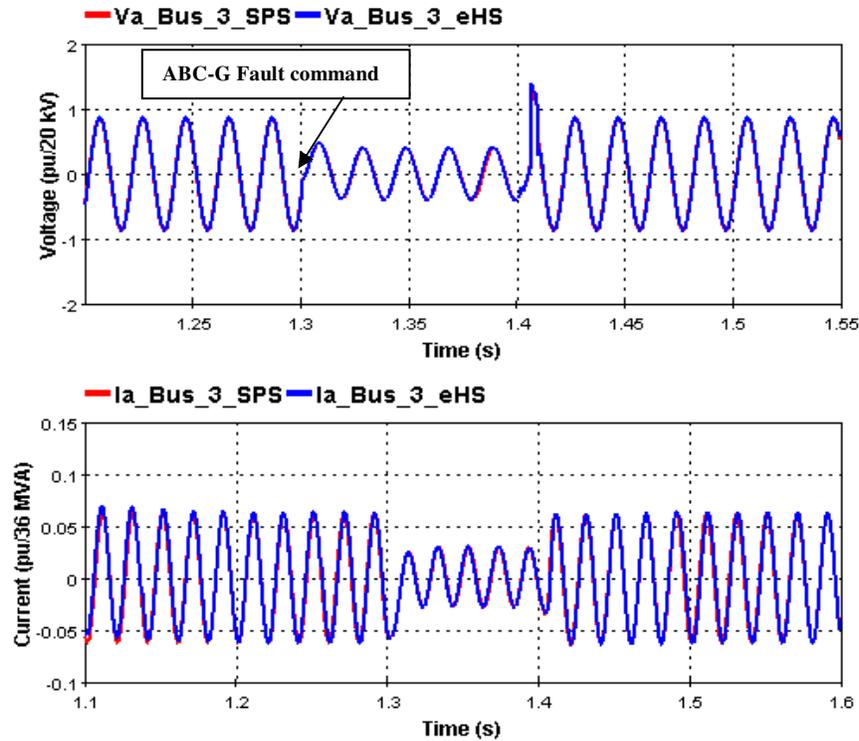
Figure 2 : real time simulation results compared to the reference SPS results, in case of ABC-G fault.

3.2   Micro-Grid Real Time Simulation Validation

The micro-grid considered in this case study consists of a battery energy storage system, a Solar panel system and some residential and industrial loads as depicted in figure 7.

Amine.yamane@opal-rt.com

3.2.1 Battery energy storage system control

The BESS system is controlled in two modes of operation:

- Grid connected mode: when the battery is connected to the network, the local power controller is triggered. The active and reactive power are regulated to match the PQ references received from the user or from a master controller managing the power flow in the system.

- Island Mode (Voltage Control): in island mode the BESS System is responsible to maintain the micro-grid voltage amplitude and frequency. The synchronization between the Microgrid and the distribution network is performed using a Phase-Lock-Loop system.

3.2.2 Solar Panel system and control

The solar panel system includes:
1. A solar panel delivering a maximum power of 250 kW at 1000 w/m2 irradiance.
2. A two-level grid-connected inverter regulating the PV voltage to get maximum solar power.

The control algorithm for the converters of the PV and the BESS systems are implemented on one of the 3.5 GHz Intel processor available in the simulator. The controller sample time was set to 10 us. Therefore, the OPAL-RT interpolation method (RT-Events) is used to generate the gates on FPGA with a frequency up to 20 kHz.

3.2.3 Micro-Grid Real time simulation results

Several tests were performed on the MG to evaluate the FPGA-Based platform to handle simulation including fast switching frequency converters. The tests performed include:

- Test 1: Transitions from grid-connected mode to the island mode under different operation points.
- Test 2: Load shedding tests in island and grid connected modes.
- Test 3: Step changes on PQ Reference in grid connected mode.

Figures 3, 4 and 5 show the results of test 3. In this test the MG is connected to the networks first by closing the MG main Breaker. Afterward, a step up on the active power reference was applied. During this test the Reactive power reference was set to 0 Var.
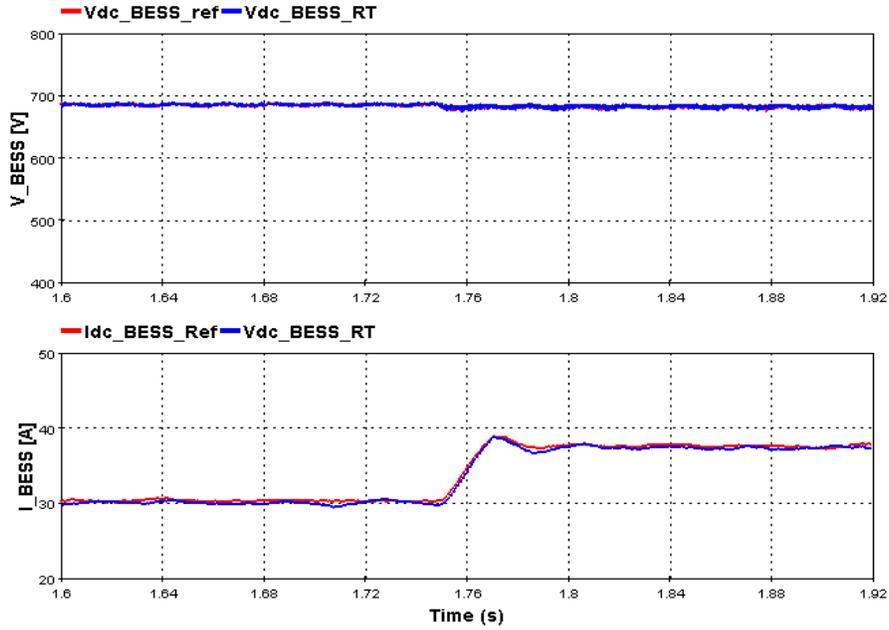
Amine.yamane@opal-rt.com

Figure 3: Test3 Results, Battery DC voltage and current
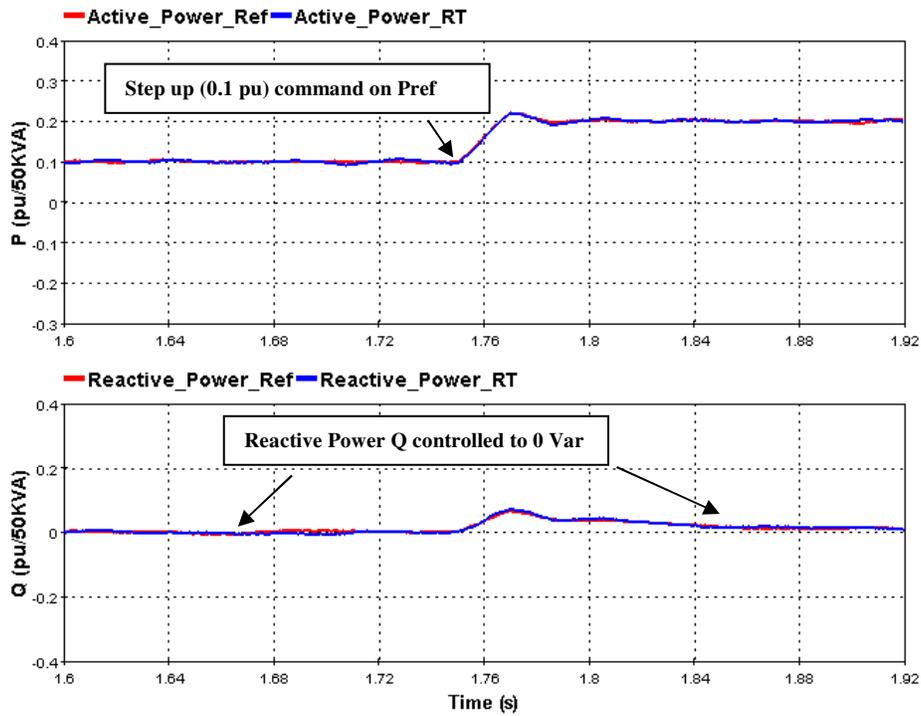
Figure 4: Test 3 Results, active and reactive power.
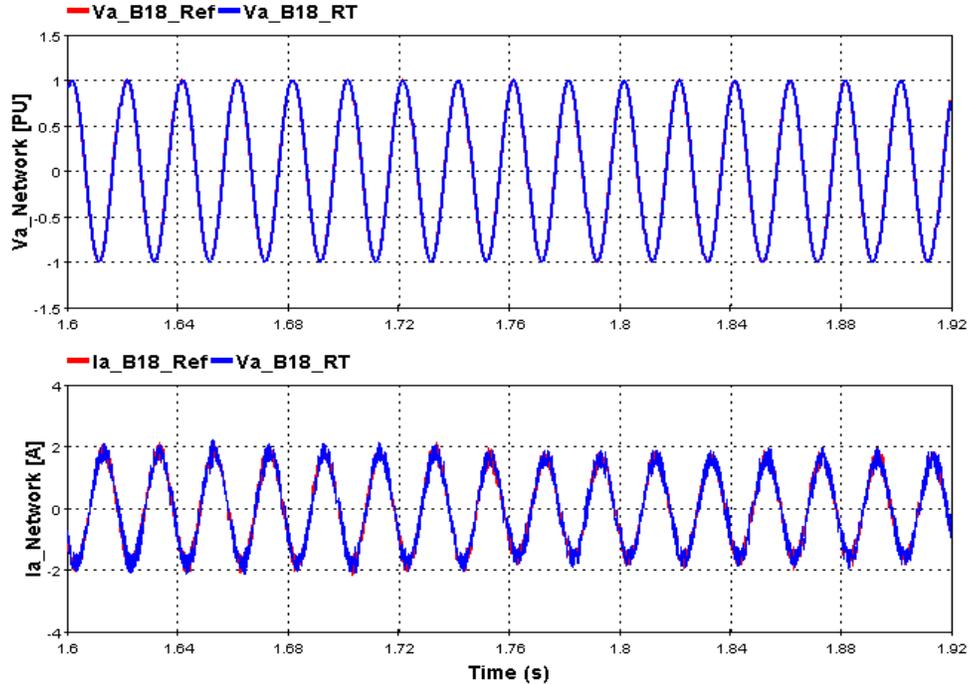
Amine.yamane@opal-rt.com

Figure 5: Test 3 Results bus 18 phase (A) voltage and current

4. CONCLUSION

This paper aimed to validate a Multi-FPGA based solution for power grid systems real time simulation. The validation was illustrated through a case study consisting of a micro-grid connected to a large distribution network with hundreds of nodes. It was shown through this circuit how we solved the two major challenges encountered: difficulty of simulating the large distribution network on several FPGA-BASED computation units, and the accuracy in simulating fast frequency switching power converters. The numerical stability of the OPAL-RT platform was validated by performing several stability tests in real time. While the accuracy of the FPGA solver was validated by comparing the real time results against a reference model developed using MATLAB and SimPowerSystems toolbox. The use of the ITM decoupling method with a sample time around 2.5 us introduces about 0.5% to 1% of the total active power, at each decoupling location. This method can be retained when simulating systems with maximum 3 or 4 decoupling locations, so the losses are limited to a total of 2 or 3% of the total active power. The distributed inductance decoupling method is slightly more complicated to integrate however, it eliminates the problem of losses introduced by the ITM method.
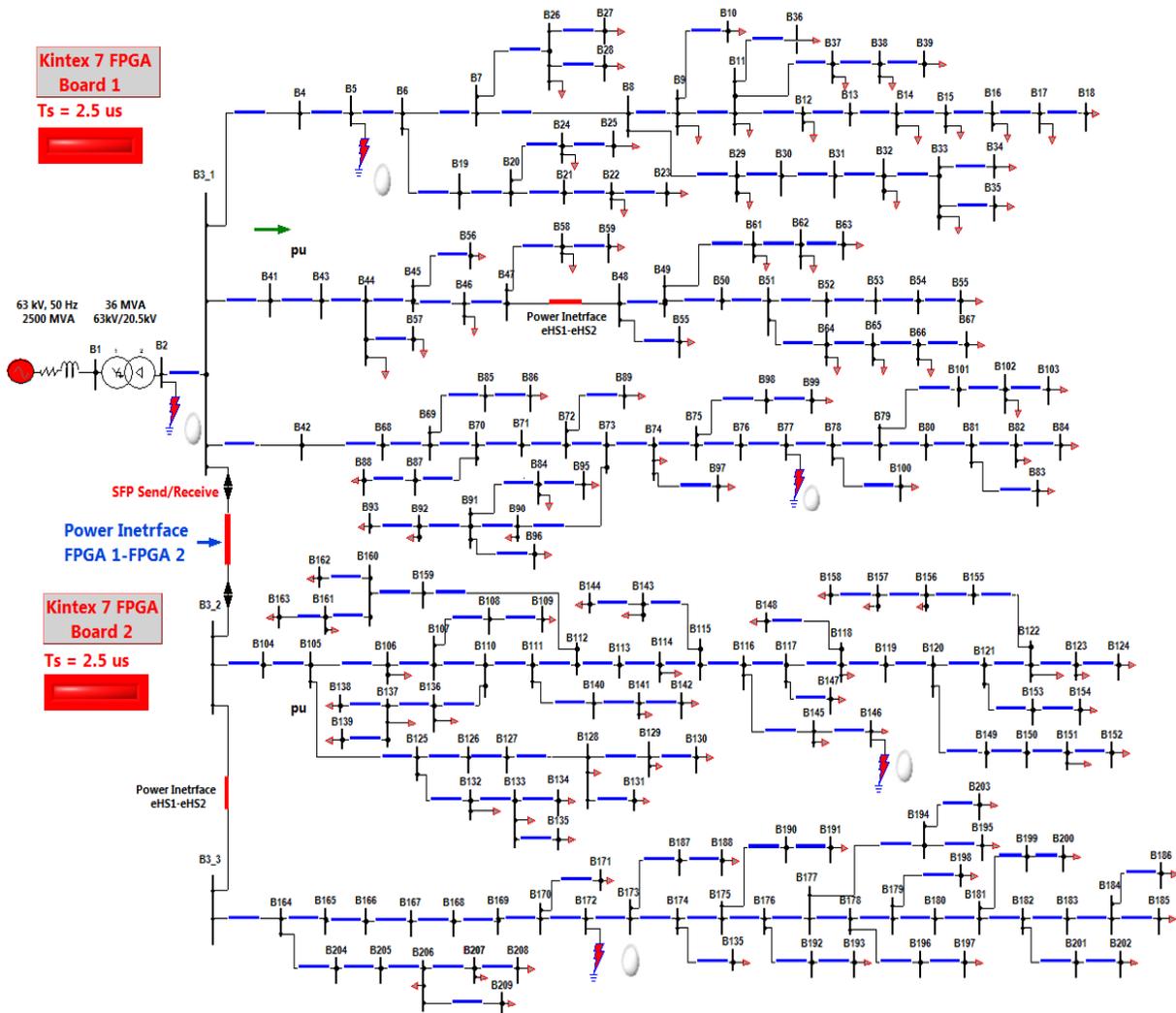
Amine.yamane@opal-rt.com

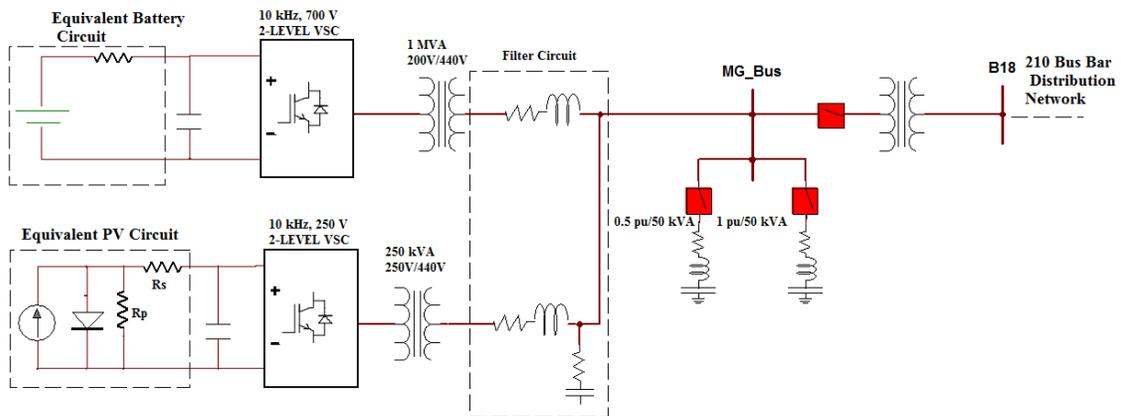Figure 6: 210 three-phase bus bars distribution network

Figure 7: Simulated Micro-Grid

BIBLIOGRAPHY

[1]   F. Guo, L. Herrera, R. Murawski, E. Inoa, C.-L. Wang, P. Beauchamp, E. Ekici, and J. Wang "Comprehensive real-time simulation of the smart grid," IEEE Trans. Ind. Appl., vol. 49, no. 2, pp. 899–908, March 2013.

[2]   C. Dufour, S. Araujo, and J. Belanger, "A survey of smart grid research and development involving real-time simulation technology," in Innovative Smart Grid Technologies Latin America (ISGT LA), 2013 IEEE PES Conference On, April 2013, pp. 1–8.

[3]   A. Teninge, Y. Besanger, F. Colas, H. Fakham, and X. Guillaud, "Real-time simulation of a medium scale distribution network: Decoupling method for multi-cpu computation," in Complexity in Engineering (COMPENG), 2012, June 2012, pp. 1–6.

[4]   F. Guo, L. Herrera, R. Murawski, E. Inoa, C.-L. Wang, Y. Huang, E. Ekici, J. Wang, and P. Beauchamp, "Real time simulation for the study on smart grid," in Energy Conversion Congress and Exposition (ECCE), 2011 IEEE, Sept 2011, pp. 1013–1018.

[5]   Ren, W.; Steurer, M.; Baldwin, T.L. Improve the stability and the accuracy of power hardware-in-the-loop simulation by selecting appropriate interface algorithms. IEEE Trans. Ind. Appl. 2008, 44, 1286–1294 [6] M. Matar and R. Iravani, "FPGA implementation of the power electronic converter model for real-time simulation of electromagnetic transients," IEEE Trans. Power Del., vol. 25, no. 2, pp. 852–860, April 2010.

[7]   D. Majstorovic, I. Celanovic, N. D. Teslic, N. Celanovic, and V. A. Katic, "Ultralow-latency hardware-in-the-loop platform for rapid validation of power electronics designs," IEEE Trans. Ind. Electron., vol. 58, no. 10, pp. 4708–4716, Oct. 2011.

[8]   Y. Levron, H. Kim, and R. Erickson, "Design of EMI filters having low harmonic distortion in high-power-factor converters," IEEE Trans. Power Electron., vol. 29, no. 7, pp. 3403–3413, July 2014.

[9]   B. Zhang, K. Zhou, and D. Wang, "Multirate repetitive control for PWM DC/AC converters," IEEE Trans. Ind. Electron., vol. 61, no. 6, pp. 2883–2890, June 2014.

[10] T. Ould-Bachir, C. Dufour, J. B´elanger, J. Mahseredjian, and J.-P. David, "A fully automated reconfigurable calculation engine dedicated to the real-time simulation of high switching frequency power electronic circuits," Math. Comput. Simulat., vol. 91, pp. 167–177, May 2013.Working Group SC 22-12 CIGRE. "The thermal behaviour of overhead conductors Section 1 and 2 Mathematical model for evaluation of conductor temperature in the steady state and the application thereof" (Electra number 144 October 1992 pages 107-125).

[11] X. Wu, S. Lentijo, A. Monti, "A Novel Interface for Power-Hardware-In-the-Loop Simulation," IEEE Trans. 2004.

[12] LA. Gregoire, " Multi-rate real-time simulation of modular multilevel converter using cpu and fpga ," École de Technologie Supérieure, April 2016.