High-Speed Hardware-in-the Loop Platform for Rapid Prototyping of Power Electronics Systems

Jason Poon, Pierre Haessig, J. George Hwang, Ivan Celanovic
Massachusetts Institute of Technology, Cambridge, MA
Email: jsn@mit.edu

***Abstract*—A hardware-in-the-loop (HIL) platform for power electronics is presented, which is based on a real-time circuit simulation algorithm and a high-throughput, low-latency processor architecture implemented in a field-programmable gate array (FPGA). By using a simulation sampling time of 1 µs, including input/output latency, the platform enables the high-fidelity, real-time simulation of power electronics systems. In addition, to realize real-time digital simulation of power electronics systems the HIL platform uses a flexible modeling environment and novel circuit compiler algorithms. The efficacy of the real-time HIL platform is demonstrated via a simulation of a variable speed induction motor drive. The results are compared with those from a real variable speed drive system under steady state operating conditions. The results demonstrate the feasibility of HIL simulation for power electronics energy conversion systems.**

I. Introduction

As the power interface between nearly all electrical sources and loads, power electronics is a key enabler for the greater proliferation of advanced green technologies such as renewable energy sources, smart grid technologies, and electric/hybrid vehicles [1]. However, with a greater use and reliance on power electronics within electrical systems, there is a need for tools to expedite their design and prototyping. For example, real-time hardware-in-the-loop (HIL) simulators allow for the testing of control software, hardware, and firmware for power electronics by replacing the real electrical or electromechanical system with a real-time emulator. This accelerates the development of advanced controllers by decoupling this task from the design and prototyping of the power electronics hardware (i.e., sources, filters, switches, and loads), which often has longer and more expensive development cycles [2]–[4]. Furthermore, other advantages of using HIL simulators include:

- a safe testing environment,
- the ability to test the full operating range for failure modes,
- repeatable testing conditions,
- flexible reconfiguration, and
- automated test environments.

While HIL simulators have been employed in numerous industries, such as automotive, aerospace, and power systems, these simulators have yet to gain a foothold in the development of power electronics systems. This is due to limitations on several fronts: i) the available computational power, ii) the algorithms/techniques used to emulate the fast switching power electronics systems, and iii) the difficulty in modeling the true non-linear and switched behavior of these systems. There are existing commercial digital real-time HIL simulators that are characterized by 50 to 100 µs time steps and computational latency, and therefore are not able to accurately simulate the very fast dynamics of power electronics systems [5]–[7].

In this paper, we present a new HIL real-time digital simulation (RTDS) platform for power electronics based on a custom designed high-throughput, low-latency processor architecture implemented in a field-programmable gate array (FPGA) and supported by dedicated application software. This platform allows engineers to build a real-time simulation of systems such as power electronics converters for variable speed motor drives, variable speed wind turbines, and photovoltaic panels. These simulation environments can be interfaced with a real hardware control unit, thus enabling extensive testing and verification over a wide range of operating conditions and system faults. The combination of the FPGA processor architecture and new modeling algorithm approach enables simulations with a fixed 1 µs time step, including input/output latency, which is at least an order of magnitude faster than current state-of-the-art systems [5]–[7].

The paper is organized in the following manner. Section II introduces the applications of hardware-in-the-loop testing, as well as state-of-the-art technologies for real-time digital simulation. In Section III, the proposed HIL real-time digital simulation platform for power electronics, based on advances in flexible piecewise linear circuit modeling and an ultra low-latency real-time digital processor, is presented. The efficacy of the new HIL real-time digital simulation platform is demonstrated in Section IV via a simulation of a variable speed induction motor drive. The results are compared with those from a real variable speed drive system under steady state operating conditions. Section V concludes the paper.

II. State-of-the-Art Hardware-in-the-Loop Technologies

Real-time digital simulation makes it possible to replace a physical system with a computer model for design and testing purposes. This enables hardware-in-the-loop testing, in which a physical controller is interfaced with a real-time digital simulation. The controller sends and receives

978-1-4244-6077-9/10/$26.00 ©2010 IEEE

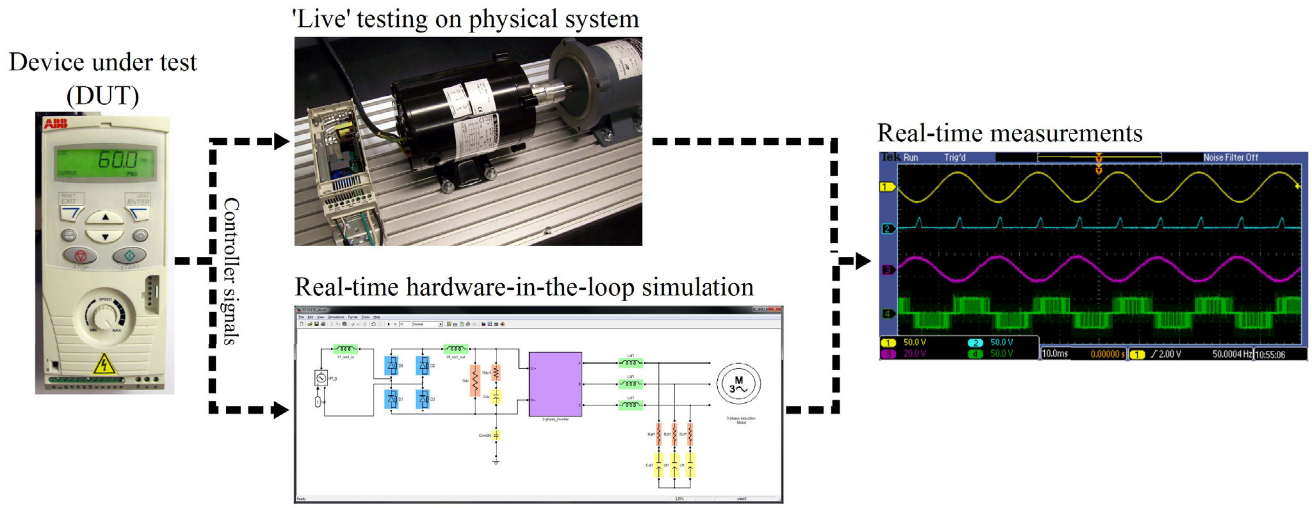


Fig. 1. A demonstration of a hardware-in-the-loop simulator (bottom) emulating the exact response of a physical system (top) in real time.

TABLE I
COMPARISON OF SIMULATION TIME STEP FOR SEVERAL COMMERCIAL HIL SIMULATORS.

HIL Simulator	Simulation Time Step
National Instruments cRIO [5]	1640 µs
dSpace DS1006 [6]	340 µs
OPAL eDriveSim [7]	15 µs
Proposed RTDS Platform	1 µs

analog and digital signals, and the real-time digital simulation responds very similarly as the true physical system would. This concept is illustrated in Fig. 1, in which a high voltage variable speed drive is emulated by a HIL simulation. We see that from the perspective of the device-under-test, there is no difference between controlling the physical electromechanical system and the real-time digital simulation. Consequently, the measured response from the physical system and real-time digital simulation is very similar.

Currently, the state-of-the-art HIL simulators for power electronics are constrained to modeling systems with low switching frequency and therefore slow dynamics. However, a majority of power converters operate well into the kHz domain such that these HIL simulators cannot accurately model the fast switching behavior and non-linear dynamics of these systems. For example, a three-phase inverter with switching frequency on the order of 10 kHz has common-mode noise transients on the order of 100 kHz. Thus, in order to properly model and observe these transients with high fidelity in real time, a real-time digital simulation with simulation time step on the order of 1µs is required. Table I compares the simulation time step, which includes input/output latency, computation time, and A/D and/or D/A conversion, of three commercial HIL real-time digital simulators with the platform we present in this paper. It is clear that commercial HIL simulators do not have the bandwidth or low latency to accurately model such a three-phase inverter in real time. The latency of these platforms degrades the fidelity of the real-time simulation such that it is impossible to observe characteristic transients and to accurately detect faults of many power electronics systems.

The proposed real-time digital simulator has a sampling time of 1µs, making it suitable for power electronics applications. In addition, its flexible platform easily allows rapid real-time HIL prototyping and testing for a wide array of power electronics systems.

III. Real-Time Digital Simulation Concept

We now introduce a new high-speed HIL platform for power electronics. This HIL platform is based on a flexible switched-mode circuit modeling approach and an ultra-low latency processor, which together enable HIL real-time digital simulation for power electronics systems.

A. Flexible Switched-Mode Circuit Modeling Approach

There have been previous investigations into real-time digital simulations for power electronics. However, many of these platforms are designed for a single fixed topology [8]–[10]. Thus, they are impractical to use as a HIL tool for rapidly prototyping new power electronics systems.

In order for a HIL platform to enable rapid prototyping, it must be flexible enough to cover a wide range of power electronics systems from a simple buck converter to a cascaded multi-level converter. Furthermore, the modeling environment must be simple and straightforward to create HIL models for these power electronics systems. This flexibility enables engineers to easily model power electronics systems and then interface power electronics controllers with the simulated model in real time.

We present an intuitive schematic editor and novel piecewise linear modeling algorithms to enable the generation of real-

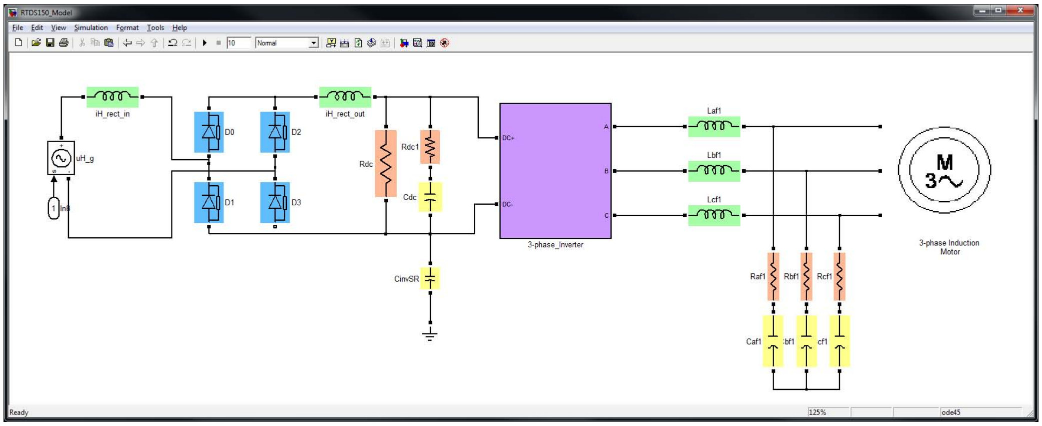


Fig. 2. A sample power electronics system described in the flexible schematic editor. From here the generation of real-time models of power electronics is completely automated.

time models for power electronics systems. This schematic editor, shown in Fig. 2, is built in MATLAB Simulink using the SimPowerSystems toolbox. This flexible environment allows users to build any switched piecewise linear RLC network. In addition, we have developed a custom HIL power electronics toolbox, which contains electrical elements such as single- and 3-phase inverters and rectifiers, as well as electromechanical subsystems such as induction machines.

The schematic is automatically compiled into a real-time model and uploaded to the HIL real-time digital simulator board. The simulations utilizes a piecewise linear modeling approach of electrical circuits based on state-space representation. Furthermore, switches are modeled as ideal switching elements while all passive elements are modeled via their respective governing equations [12]. This enables the accurate simulation of both the switching transients and continuous dynamics of power electronic systems within a 1 µs deterministic execution time-step.

B. Ultra-Low Latency Processor Architecture

The FPGA processor architecture of the HIL platform allows the simulation of a wide variety of power electronic models, while also delivering the same high performance as existing dedicated fixed-topology solutions. Combining the glue logic and processing engine in a programmable structure of an FPGA device enables a loop-back latency on the order of 1 µs, as shown in Fig. 3, which is one of the key differentiators of this technology over existing HIL solutions.

Together, the flexible model compiler for power electronic systems and low-latency real-time digital processor form the basis for a novel HIL platform the enables the rapid design and testing of power electronics systems.

IV. Experimental Demonstration of Hardware-in-the-Loop Platform

In this section the performance, speed, and fidelity of the new HIL platform is demonstrated via a one-to-one comparison with an experimental drive system.

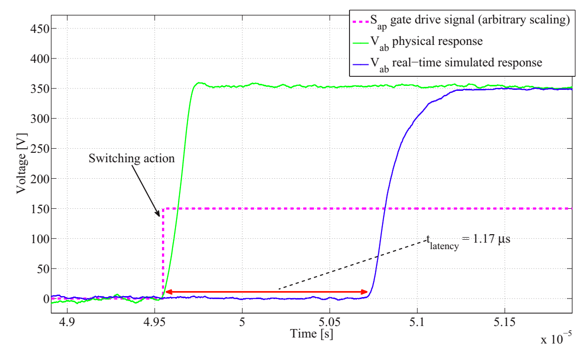
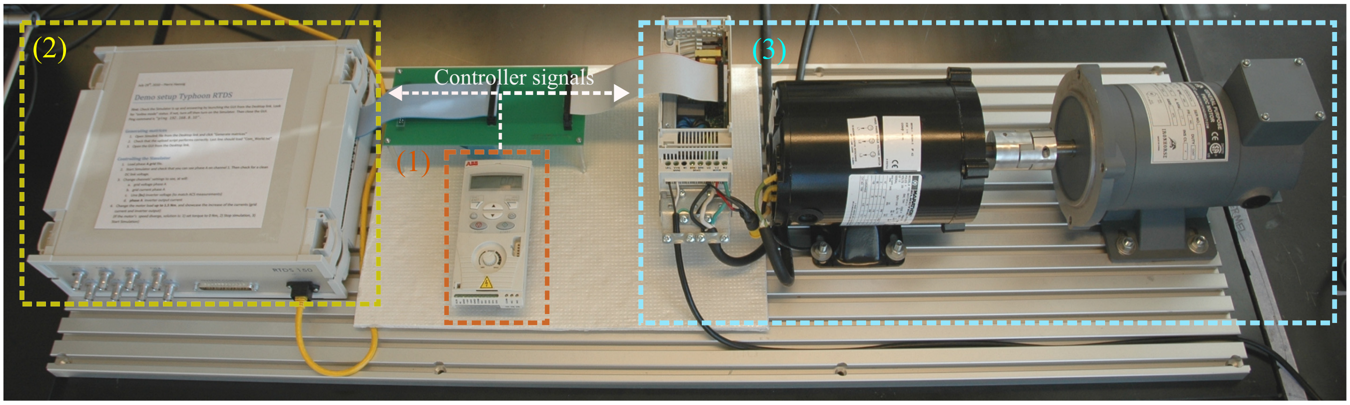


Fig. 3. A three-phase inverter line-to-line voltage response to a gate drive signal. Latency on the order of 1 µs is demonstrated by the real-time digital simulation.

A. Description of Experimental Setup

In order to demonstrate the performance of the real-time HIL platform, we test an industrial grade open-loop variable speed drive (ABB ACS-150) controller connected to a squirrel-cage induction machine as a case study. A picture of our experimental setup is shown in Fig. 4. The efficacy and accuracy of the HIL platform is demonstrated by comparing the response of the HIL simulation with the response of the real system. Both the real-time simulation and the physical system are controlled by the same power electronics controller. The outputs from the simulator and the measurements from the physical system are measured and compared.

A custom designed breakout board is used to connect two parallel systems to the same controller. The first system is the physical ABB ACS-150 variable speed drive [13]. The ACS-150 is a 0.5 HP, 3-phase 240 V inverter with a switching frequency up to 16 kHz. The ACS-150 drive is connected to a three-phase, four-pole, squirrel-cage induction machine. This induction machine is mechanically coupled to a DC machine to test the power system at different operating load points. The second system is the HIL real-time digital simulation board, which emulates the ACS-150 variable speed drive and

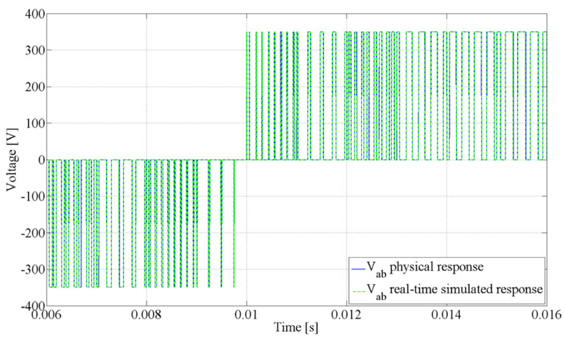


(2) HIL platform simulating variable speed drive connected to three-phase

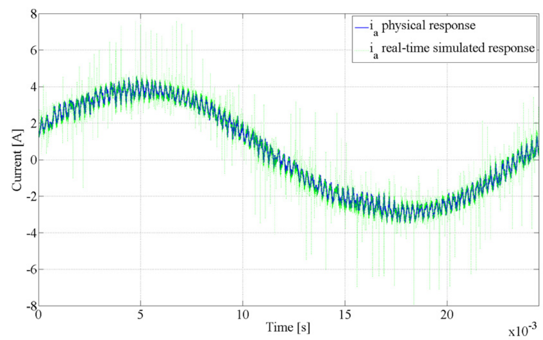
(1) ACS-150 variable speed drive controller. Device-under-test (DUT)

(3) Variable speed drive converter connected to three-phase induction machine.

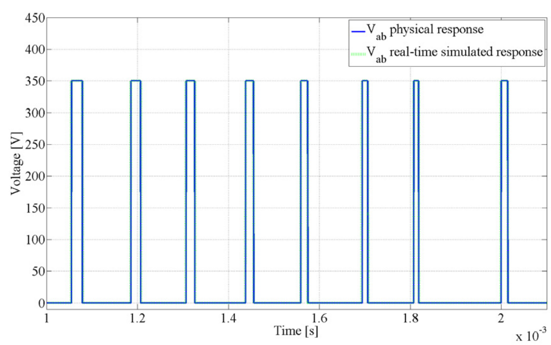
Fig. 4. The experimental setup used to make a one-to-one comparison between the physical system modeled in the real-time digital simulator and the real-time digital simulator itself.



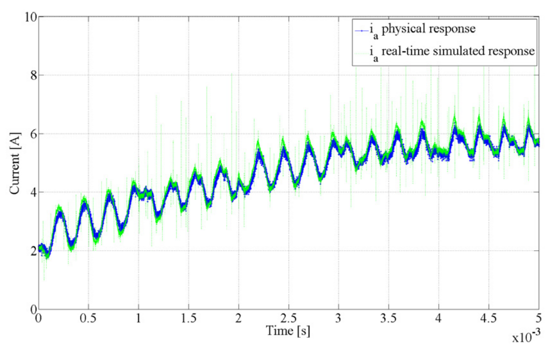
(a) Line-to-line voltage v_{ab}



(a) Phase-A line current i_a



(b) Zoom-in of line-to-line voltage v_{ab}



(b) Zoom-in of phase-A line current i_a

Fig. 5. Line-to-line voltage comparison between the inverter output of physical drive system and output from real-time digital simulator.

Fig. 6. Phase-A current comparison between the inverter output of physical drive system and output from real-time digital simulator.

induction machine.

B. Experimental Results

In Figs. 5 and 6, we show a one-to-one comparison for two different measurements, inverter output line-to-line voltage v_{ab} and phase-A current i_a, respectively. It is evident that the response of the real-time digital simulation matches closely to the measured physical response of the system. As a result of the 1 μs simulation time step, the real-time HIL simulator is able to capture the dynamics of the electromechanical system on the microsecond scale.

From Fig. 5, we see that the ultra-low latency of the real-time digital simulator enables the precise modeling of fast switching actions occurring on the order of 10 kHz. Examining Fig. 6, it is clear that the real-time HIL simulator is able to model the transients in the inverter output phase current with high-fidelity. This case study validates the new HIL platform as a ultra-fast and high-fidelity tool for simulating fast-switching power electronic systems in real-time.

V. Conclusion

This paper presents a new flexible hardware-in-the-loop platform for high-power, fast-switching power electronics systems. This real-time digital simulator can emulate power electronics systems with a 1µs simulation time step including input/output latency, computation time, and A/D and/or D/A conversion. This enables the fast and accurate real-time simulation of high power electronic systems which are highly non-linear dynamic systems. The HIL platform is based on innovations in switched piecewise linear circuit modeling for real-time simulation and an ultra-low latency FPGA processor. The new HIL platform enables the rapid prototyping and testing for power electronics control software, hardware, and firmware.

As power electronics continue their rapidly expanding proliferation into electrical energy systems, design and testing tools become increasingly necessary to validate and optimize these systems. The new HIL platform serves as a tool to significantly reduce design and development cycles, provide increased reliability in end systems, and enable increased efficiency and performance.

References

[1] W. Reder, A. Bose, A. Flueck, M. Lauby, D. Niebur, A. Randazzo, D. Ray, G. Reed, P. Sauer, and F. Wayno, “Engineering the future: a collaborative effort to strengthen the U.S. power and energy workforce,” *IEEE Power Energy Mag.*, vol. 8, no. 4, pp. 27-35, Jul./Aug. 2010.

[2] A. D. Dominguez-Garcia and P. T. K. Grainger, “A framework for multi-level reliability evaluation of electrical energy systems,” in *Proc. IEEE Energy 2030 Conference, ENERGY 2008*, Atlanta, GA, USA, Nov. 2008, pp. 1-6.

[3] J. Mahseredjian, V. Dinavahi, and J. A. Martinez, “Simulation tools for electromagnetic transients in power systems: overview and challenges,” *IEEE Trans. Power Del.*, vol. 24, no. 3, pp. 1657-1669, Jul. 2009.

[4] S. Khomfoi, L. M. Tolbertt, and B. Ozpineci, “Cascaded H-bridge multilevel inverter drives operating under faulty condition with AI-based fault diagnosis and reconfiguration,” in *Proc. IEEE International Electric Machines and Drives Conference, IEMDC 2007*, Antalya, Turkey, May 2007, pp. 1649-1656.

[5] “Benchmarking single-point Performance on National Instruments real-time hardware,” July 2010. Available: http://zone.ni.com/devzone/cda/tut/p/id/5423

[6] “dSPACE launches world’s fastest HIL simulation technology,” February 2007. Available: http://findarticles.com/p/articles/mim0EIN/is2004Feb26/ai113638607/

[7] “Opal-RT introduces eDRIVEsim real-time HIL simulator control prototyping platform,” October 2007. Available: http://www.opal-rt.com/press-release/opal-rt-introduces-edrivesim-real-time-hil-simulator-control-prototyping-platform

[8] L.-F. Pak, V. Dinavahi, G. Chang, M. Steurer, and P. F. Ribeiro, “Real-time digital time-varying harmonic modeling and simulation techniques,” *IEEE Trans. Power Del.*, vol. 22, no. 2, pp. 1218-1227, Apr. 2007.

[9] Y. Li, D. M. Vilathgamuwa, and P. C. Loh, “Design, analysis, and real-time testing of a controller for multibus microgrid system,” *IEEE Trans. Power Electron.*, vol. 19, no. 5, pp. 1195-1204, Sep. 2004.

[10] X. Wu, H. Figueroa, and A. Monti, “Testing of digital controllers using real-time hardware in the loop simulation,” in *Proc. IEEE 35th Annual Power Electronics Specialists Conference, PESC 2004*, Aachen, Germany, Jun. 2004, pp. 3622-3627.

[11] A. Makinen and H. Tuusa, “Wind turbine and grid interaction studies using integrated real-time simulation environment,” in *Proc. Nordic Workshop on Power and Industrial Electronics, NORPIE 2008*, Espoo, Finland, Jun. 2008.

[12] J. Allmeling and W. Hammer, “PLECS-piece-wise linear electrical circuit simulation for Simulink,” in *Proc. IEEE 1999 International Conference on Power Electronics and Drive Systems, PEDS 1999*, Hong Kong, Jul. 1999, pp. 355-360.

[13] Catalog No. ACS150-PHTC01U-EN, *ABB Component Drives: ACS150, 0.5 to 5 Hp*, ABB Inc., New Berlin, WI, USA.