Cyber Physical Systems Approach to Power Electronics Education

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Abstract—**This paper proposes a Cyber Physical Approach (CPS) to power electronics (PE) education where all aspects of PE technology from circuit topology to the implementation of real time control code on a microprocessor are dealt with as an inseparable whole, and only the system complexity is increased during the course of instruction. This approach is now made practical thanks to the affordable and unrestricted access to high-power PE laboratory infrastructure (PE laboratory in a box) in the form of high-fidelity digital PE emulators with 1□s calculation time step and latency.**

Index Terms—**Cyber physical systems, hybrid systems, hardware-in-the-loop, power electronics education.**

I. Introduction

Cyber physical systems (CPS) or the computer augmented physical systems range from the miniscule-scale e.g. hearing aid to very-large-scale e.g. the national power grid [1]. At the same time they may well be the largest and fastest growing class of manmade systems with inexhaustible potential for further development.

The power grid, which is the largest CPS system (or any many made systems), is currently undergoing a massive transformation from vertically integrated to open-access, decentralized, market driven, dynamical system [2]-[4]. To make things more interesting the distributed renewable power generation assets, the deregulation, and the increased number of smart power electronics devices are all simultaneously and from different directions reshaping the grid [5].

In all this development power electronics (PE) is playing the role of enabling technology, providing means for precise and reliable power flow control between the grid and the majority of its distributed sources and loads as well as between parts of the grid itself through wider use of flexible-ac-transmission (FACTS) PE devices [6]-[8].

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Clearly, all this development calls for new tools and methodologies that can support all the massive new development currently under way in various aspects of the smart grid.

A. Power Electronics Hybrid Systems

Switched circuits in power electronics exhibit pronounced hybrid systems behavior because they are best described by a set of discrete states with the associated continuous dynamics, where the controller reaches its control objectives by choosing among the discrete states [9]. Because there is a large number of discrete states (and even larger number of transitions) even for relatively small power electronics systems the exact analysis and understanding of the system is difficult. This is also the reason why the commonly taught techniques for analysis, control and simulation of PE systems involve considerable approximations which limit their accuracy.

Typically, the switching circuit is averaged, and than linearized around the operating point which makes the circuit manageable but neglects the important circuit dynamics as well as the circuit's nonlinear behavior. The control synthesis is accomplished by means of linear control techniques, and finally the resulting system's performance is evaluated on the switched circuit simulation and on the hardware models.

B. Limited Access To High-Power PE Infrastructure Limits the Quality of PE Education

The common limiting factor in all smart grid education in general and PE in particular is the limited access to PE hardware (particularly high-power hardware), or preferably the real-time emulation facilities with sufficient time resolution: for medium to high power PE systems the time resolution of 1μs or less is required [10].

The simulation packages like Mathworks's SimPowerSystems (and others) behavioral models of power hardware are rather accurate in all but the time domain. In other words, they cannot be connected directly to the real time controller, and operated in real time.

Thanks to the automatic code generation technology like Mathworks's Real-Time Workshop it is now possible to generate the micro controller C-code from Simulink which is an admirable step forward in the process of control algorithms code generation. Still, the microcontrollers architectures are far from powerful enough to emulate the power electronics hardware by means of automatic code generation [11].

As the digital controllers are an integral part of the PE CPS

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systems it is important that they become an integral part of the PE education at all levels and to a much higher degree than is presently the case. Still, before that can be done access to high-power PE laboratory facilities must be made available at a massive scale, and at the fraction of the cost.

C. High-Power Laboratory in a Box as a Way to Bring CPS Approach to PE Education

Fig. 1 shows the digital controller connected to a real-time model of the physical system with the calculation time step of 1µs. The scope of the real time physical systems models includes models of the electric grid, PE converters, filters, electric machines, photovoltaic panels and passive elements [11].

The hardware of the modeling platform has a small form factor, is universal, reconfigurable and very easy to use. It offers the full insight into the inner working of PE hardware (including grid, machines, filters…) to a higher degree than even the actual hardware setup can offer (and in many cases more accurate). With 1µs time resolution it captures all the dynamics of interest for the PE systems in the range from a kW to 100MW.

Such an emulation platform (HIL in the remainder of the text) has potential to offer an unlimited access to high-power “hardware” to a very large number of students at all levels of education: from undergraduate to post-doctoral level.

All what is needed is a low cost processor evaluation board, HIL (a high-power laboratory in a box), and an oscilloscope, and the students can start acquiring their hands-on “high-power” experience.

II. The HIL Based Curriculum

An unlimited access to “high power laboratory” allows instruction of various aspects of PE design within the CPS frame. This would be a holistic approach, an alternative to studying PE topologies, machines, modulation techniques with fault protection, closed loop control techniques, thermal issues, microprocessor programming techniques and PE lab as separate courses [12]-[14]. With HIL technology it is now possible to study all the mentioned issues within the “living” and “breathing” system. Following this approach the students would work thorough various engineering topics of simpler systems first and then gradually delve into more complex systems and engineering issues while maintaining the holistic CPS view.

A. Introductory Undergraduate Education

Following the proposed CPS approach to PE course of instruction the student’s first contact with PE would be at the level of complexity of a dc/dc boost converter from Fig. 2 running in the open loop, with the PWM generated in the digital controller.

Such a simple circuit example is an excellent way for the students to get acquainted with the HIL and micro-processor tool chain first and through that process get the hands on experience and the feeling for the continuous and discontinuous mode of operation and effects caused by the variation of line and load conditions, components parameters and losses in the switching devices; all this without the single equation written and with a CPS viewpoint.

Only then, after creating the initial interest the instruction can go into theoretical concepts (mathematics) of the circuit operation, the circuit can be linearized and discretized and the loops closed, on the digital control platform that students are by this point fully familiar with.

B. Advanced Undergraduate Education

With the basic concepts covered on the examples of dc/dc converters in the advanced course the vector control of motor drive shall be studied, together with the machine modeling topics and two and four quadrant grid connected converter arrangements. Hardware part of induction motor drive could be described as in a Fig. 3 using schematic editor. Control part could be developed using different kind of control development platforms such as Texas Instruments or Microchip. These control algorithms should be automated to the level that students are able to independently study above mentioned topics at the system level.

C. Graduate Level Research

At graduate level it is up to the imagination of the researchers to extend the state of the art in sensorless vector control drives, automated testing, harmonic optimization of grid connected converters for the case of the disturbances on

Fig. 1. Universal CPS platform.

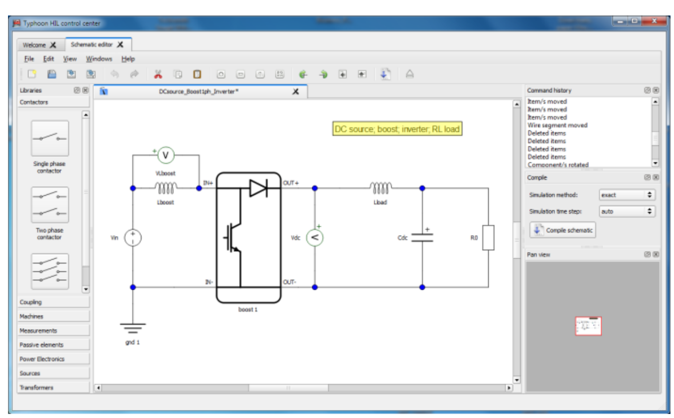

Fig. 2. Schematic editor view of the boost-converter circuit.

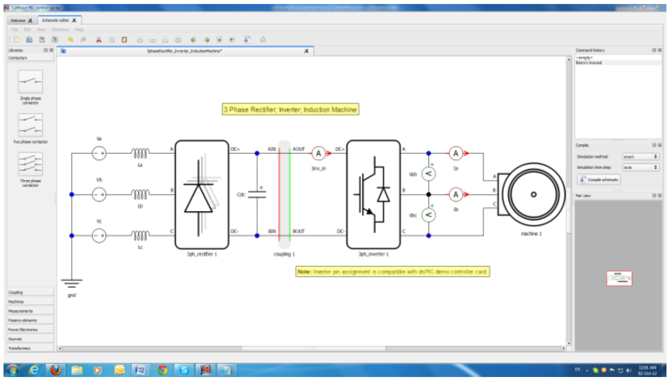

Fig. 3. Schematic editor view of the induction motor drive application.

the grid (Fig. 4), develop fault tolerant and robust control etc. HIL emulation platform replaces real hardware and enable researches to easily and in safe environment enrich their research. Different control techniques in various real conditions could be studied and implemented. Doing it this way students gain invaluable experience working on the real system instead of doing only simulation in Matlab like it was in past.

III. The HIL and Its Accessories

The proposed HIL with its accessories [11] is a closed out-of-the-box systems that requires no third party tools, or hardware accessories to develop the curriculum.

The HIL platform is based on a scalable, custom, ultra-low latency processor design implemented on FPGA and optimized for a circuit-modeling approach where the switches are modeled as ideal switches, diodes as ideal diodes and RLC elements as linear elements. While most of the commercial processors available today tend to achieve high levels of computing power, the proposed ULL HIL processor targets low computational and IO latency. This approach results in a design that allows combined computation time and I/O latency of the order of 1μs for typical 2 and 3-level PE topologies. With such a short latency, the switches will respond as quickly as in a real converter (turn-on and off times for 1200 and 1700V IGBTs are about 1 and 2μs respectively). Hence, the achieved total latency of 1μs is in accordance with the requirements reported in the literature for high-speed HIL converter simulators [15]-[17] regarding simulation sampling frequency, simulation frequency/PWM frequency ratio, as well as I/O system latency.

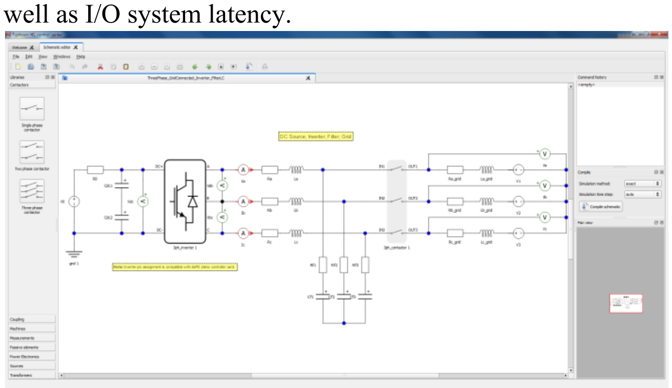

Fig. 4. Schematic editor view of the grid connected inverter application.

The presented HIL platform (Fig. 1) [18] is flexible enough to cover a range of power electronics systems and in this way facilitates rapid system-prototyping. Furthermore, the modeling environment, using a graphical user interface, is easy and intuitive to use.

Discrete-time processing and high fidelity are essential features for PE applications because of their non-linearities and intrinsic switching nature. The proposed HIL emulator utilizes time-discrete processing of the system model. In contrast to time-averaging methods, this approach requires very high fidelity in the time-domain, fine time-resolution and very low latency.

A. HIL Toolchain

The software Tool-chain includes a Schematic Editor (Fig. 2), Circuit Compiler and Emulator Control Panel (Fig. 5). These tools provide a flexible environment for model editing, offline compiling (into the form needed by the processor) and managing the emulation. They are installed on a standard Windows operational system.

The Schematic Editor comprises a library of switching models of PE elements and linear models of electrical machines, electrical sources and passive elements. It allows users to build a variety of configurations combining library elements. The PE components are modeled as ideal switches, while all passive-element models are represented by their respective governing equations.

The user can define arbitrarily any shape of input voltage and current sources using Waveform Generator. At the Fig. 5 generator of photovoltaic (PV) panel curves is displayed.

The HIL controller provides an easy way to assign signals and their scaling to IO pins, load grid waveforms, make a preview of grid waveforms, start and stop the HIL emulation, specify motor load torque and several more standard applications which enable comfortable user environment.

B. HIL Hardware

HIL hardware shown in Fig. 7 is compact, powerful and versatile system that can emulate a number of topologies and parameter variations of PE circuits. The IO comprises:

- 96 pin digital connector with
  32 digital inputs, and
  32 digital outputs, as well as

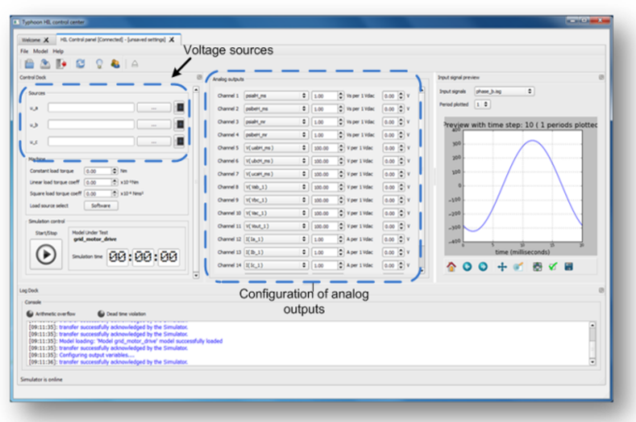

Fig. 5. HIL controller.

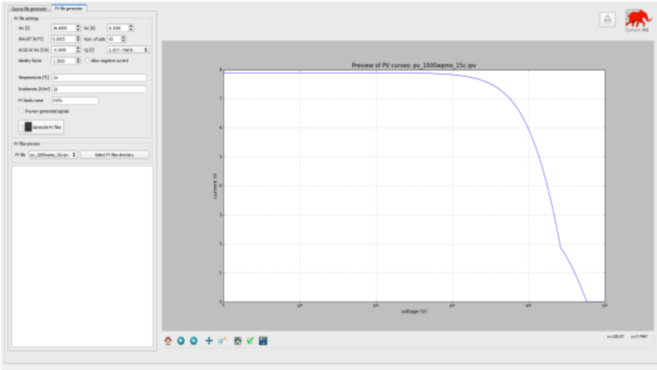

Fig. 6. PV panel curves generator.

Fig. 7. High power laboratory in a box (HIL).

- 64 pin analog connector with
  16 analog output, and
  8 analog inputs.

Each IO is programmable and can be assigned to any pin within its group.

Proposed HIL uses standard DIN 41612, type C connectors. In order to simplify external signal conditioning electronics the HIL output provides on its AIO and DIO connectors

- +/-5V, +/-12V analog power, and
- +3.3V and +5V digital power.

C. *HIL Accessories*

There is a number of controller accessories available for HIL in order to enhance the proposed CPS's user experience, and eliminate the systems setup time. The controller board delivered with the HIL is based on the Microchip dsPIC30F4011, is easy to program, has a free to download tool chain and is powerful enough to control a wide range of applications. This simple evaluation platform (Fig. 8) allows the students to gain controller testing experience "straight-out-of-the-box". It is an excellent introduction-level PE controller and is well suited for PE controls training. There are 19 digital output pins on the board; 6 PWM signals and 3 encoder signals are connected directly to the IO connector, while the remaining 10 pins are general-purpose user-configurable, i.e. as digital input/output, push-buttons or LEDs.

Four analog inputs receive signals in the range of ±5V and can be connected to the board using a 0.1", 10-way IDC connector. The programming interface mates directly with a PICkit2 programmer from Microchip. The board is connected via the PC graphic user interface of Fig. 10 through a serial RS232 interface.

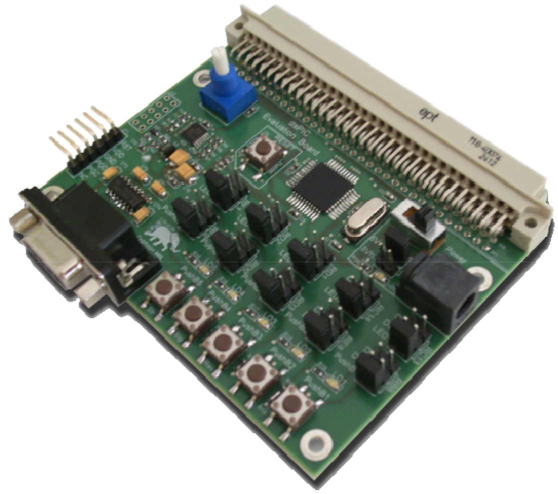

Fig. 8. Introductory level controller board.

Even more powerful accessories are HIL Docking Stations for Texas Instruments DIM100 control cards and eZdsp 2808 and 2812 platforms (Fig. 9), HIL Docking Station for Analog Device Blackfin BF506F, as well as HIL Docking Station for dSpace ds1104. Using HIL and those accessories immense possibilities in CPS are opened.

Employing docking station together with HIL, user can simply develop and test the real controller using HIL as a power stage and DSP as a controller platform. If we take into account that Texas Instruments has a large and highly educative library of different PE applications, it is clear that HIL and DSP combined together bring new possibilities in CPS. The user simply chooses PE application from TI DSP library assembles the electrical scheme of the power stage in the HIL Schematic Editor and in several clicks the PE drive is running. Proposed HIL has Graphical Interface for several examples of control from TI DSP Library, like Sensored IFOC Induction Motor Drive (Fig. 10). Users can observe, change control parameters and test the operation of the drive in "normal" conditions as well as in fault states and different kind of disturbances like faults, voltage sags, harmonics, swells, etc.

The supported DIM100 Control Cards are: F2808, F28044, Delfino F28335, Piccolo F2803x, Piccolo F2806x and Concerto F28M35xx.

For undergraduate education, particularly suitable is the combination of the HIL and dSpace platform [19] (Fig. 11). In such scenario, the control algorithm can be developed on dSpace platform using Matlab and Simulink. This is very convenient for students that are still not familiar with DSP

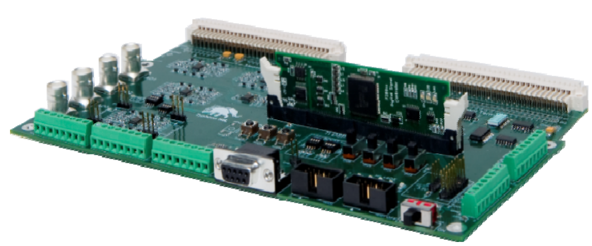

Fig. 9. HIL Docking Station for TI DSP.

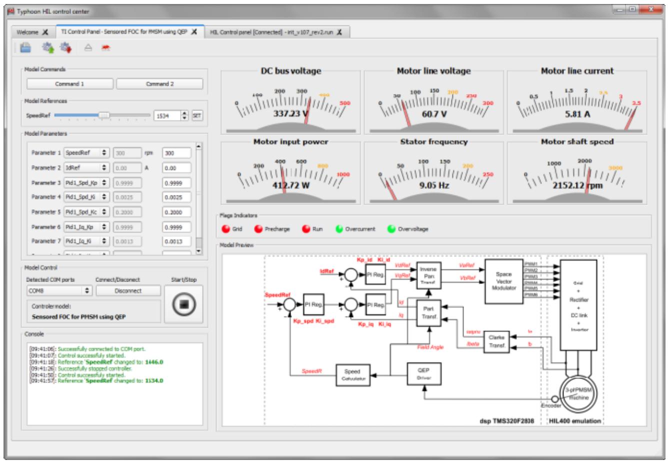

Fig. 10. Graphical interface for TI DSP library.

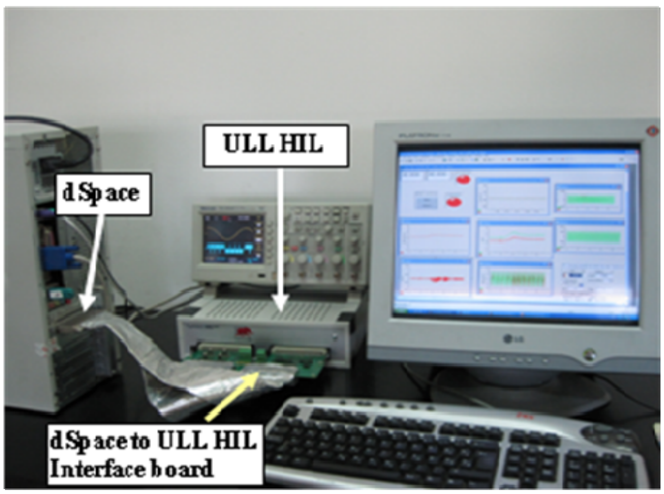

Fig. 11. CPS based on HIL and dSpace.

platforms and programming in C-based environment.

IV. Conclusions

This work proposes a CPS approach to power electronics education made possible by the recent advances in PE emulation technology which enables completely flexible, affordable and unrestricted access to fully reconfigurable PE hardware. Numerous steps are currently under way to further develop this approach. The HIL libraries are developed further, accessories designed and curriculum material developed in the collaboration between the producer of HIL equipment and some reputable universities.

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