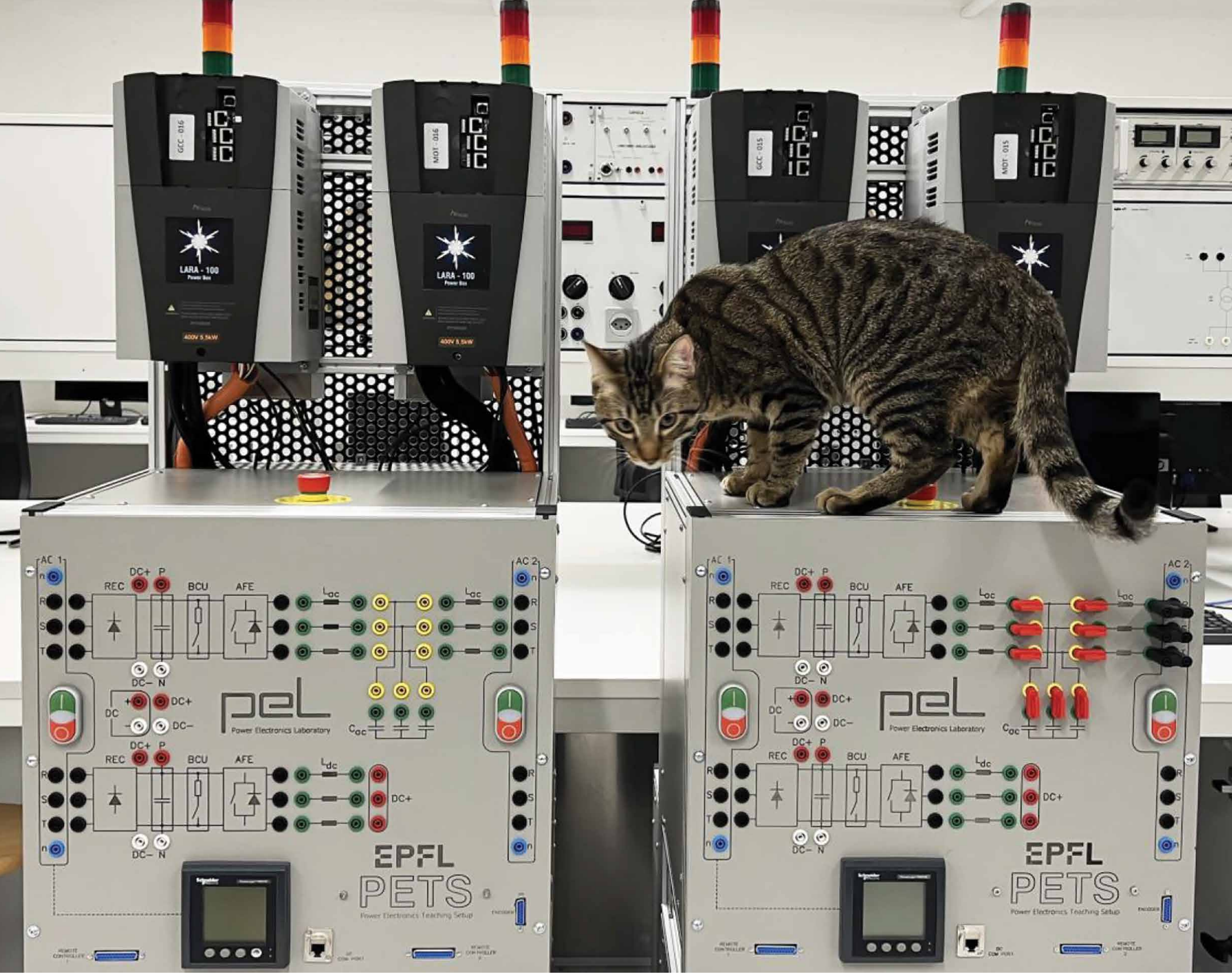

Learning With Your PETS

by Drazen Dujic, Andrea Cervone, Renan Pillon Barcelos, Jules Mace, and Max Dupont

Recently, we published an article [1] presenting how the Power Electronics course at the bachelor level is organized by the Power Electronics Laboratory and taught at Ecole Polytechnique Fédérale de Lausanne, EPFL, Switzerland. For those avid readers who may have checked the article, it may be clear that the main topic of that course aims to teach students practical hardware design. But, this is only a subset of the power electronics field, and there is much more to it. Namely, modern power

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electronics rely heavily on the digital control and use of computational resources such as microcontroller units (MCUs), digital signal processors (DSPs), or field programmable gate arrays (FPGAs), to name a few. As power ratings and complexity of the converters are increased, one must resort to using embedded controller hardware, and develop and deploy suitable control algorithms on it.

With the evolution of the size and performance of power management integrated circuits (PMICs) and embedded controllers, their use in education has evolved as well. Many examples of the organization of laboratories have been reported over the years [2], [3], [4], from where one can clearly recognize and track the technological evolution, change of learning focus, tools, and methods used.

The field of control is extremely important in power electronics and is an important part of the curriculum in electrical engineering in all universities. With a huge and ever-increasing number of applications that rely on power electronic converters and a plethora of embedded controller hardware options, one has to decide what are the relevant learning objectives and how to achieve them with available tools, equipment, and hours available in the curriculum.

This article presents the approach and tools used by the Power Electronics Laboratory at EPFL when it comes to teaching digital control in power electronics, mainly prosecuted at the master's level. Learning objectives and paths taken to achieve them are presented in a general way, while more details are presented regarding the equipment that is developed to support the courses and provide a rich learning experience for the students.

Learning Objectives

Numerous applications nowadays use power electronics converters to achieve efficient, fast, and controlled energy conversion. Increased deployment of renewable energy generation, battery energy storage, and electric vehicles are all characterized by multi kW or MW ratings, and various converter topologies and control methods are out there. It is not possible to cover them all, so courses are organized in a way to teach students "*digital control principles applied to power electronic converters*," particularized for a given conversion problem in some popular applications.

Hence, the main emphasis has been focused on grid-connected converters, covered and motivated by photovoltaic (PV) generation principles, and on high-performance variable speed drives used in electrical mobility or wind energy generation. Both application areas, while tackling different conversion problems and requirements, share many identical background concepts and implementation aspects.

Common themes for each of these areas are converter topologies and their operating principles, as well as various pulse-width modulation (PWM) methods, like carrier-based PWM and space-vector PWM approach. Closed-loop control principles are also extremely relevant and are mainly implemented considering proportional-integral-derivative (PID) and proportional-resonant (PR) types of regulators, covering their operating principles, tuning methods, anti-windup techniques, etc. Finally, control implementation is presented and analyzed in different reference frames: phase variable domain (abc), stationary reference frame (α-β), and rotational reference frame (d-q).

At the same time, it is also possible to analyze concepts that, despite being more application-specific, are still of paramount importance in practical implementations. For example, considering PV generation and grid-connected-converters, topics such as phase-locked loop (PLL) principles for both balanced and unbalanced grid conditions, P-Q control and power quality, and maximum power point tracking (MPPT) algorithms are typically covered in detail.

On the other hand, topics related to high-performance variable speed drives include modeling of various electric machines (dc, synchronous, induction), principles of decoupled flux and torque control, scalar control, field-oriented control, and direct torque control principles. Maximum torque per ampere (MTPA) algorithms and flux-weakening approaches are also covered as well.

In summary, the focus is on understanding and applying mentioned control techniques to power electronics converters. The goal is to implement them to serve defined application needs and validate the theoretical principles experimentally.

Power Electronics Teaching Setup

To support the previously listed topics with a hands-on practical experimental experience, a dedicated Power Electronics Teaching Setup (PETS) has been developed, as shown in Figure 1. It integrates ac and dc power sources and two power electronics converters with a few surrounding passive and active elements. It has been specifically designed to allow various circuit reconfigurations on the front panel, in a way to offer a flexible platform that could be easily adapted to different applications. As of today, 22 PETS units have been manufactured for our teaching needs in the already-mentioned fields of interest.

The PETS is supplied from a 3×400 V, 50 Hz network, and the three-phase source, labeled AC 1 on the front panel (highlighted in Figure 1) is realized by means of an isolating transformer followed by a manually operated variable autotransformer. This allows adjusting the AC 1 voltage level for different exercises, while the installed power meter on the panel allows users to keep track of voltages, currents, powers, harmonic distortions, etc. DC supply is achieved by an SM660-AR-11 power supply by DELTA ELEKTRONIKA [5], mainly selected for its ability to be programmed both as a controllable voltage/current source and as a PV emulator. In normal use as a power supply, it can directly energize the dc links of the power electronic converters. The second source, labeled AC 2 on the panel, allows for direct connection to a laboratory high-power four-quadrant grid emulator TC.ACS by REGATRON [6], allowing for identical grid voltage conditions to be made for many PETSs connected to that locally created microgrid.

FIG 1 Power Electronics Teaching Setup (PETS) with highlighted front panel.

Some passive components are also integrated into the PETS. Three dc inductors are connected to the active side of one of the converters, mainly for the purpose of dc–dc conversion, with or without interleaving operation (e.g., as Boost converter performing MPPT algorithm from an emulated PV source). Two three-phase ac inductors, together with ac capacitors can form an L (with two different values) or LCL filter for the grid-connected converter-related exercises. Additional external elements can be easily introduced through the front panel connection. For example, if passive damping of the LCL filter is desired, it can be achieved by connecting external damping resistors in series to the filter capacitors through the panel insertion points.

Finally, the key parts of the system are two converters, that started their life originally as HYUNDAI N700 frequency converters for variable speed drives. They are rated for 400 V_{ac} and 5.5 kW and feature a three-phase diode rectifier, an integrated dc-link capacitance, a braking chopper, and a three-phase two-level voltage source inverter, all as part of the intelligent power module, rated for 1200 V and 35 A. The external braking resistors are integrated into the PETS, allowing for the use of the chopper legs on demand, for various test or control functions. When needed, two dc links can be directly connected in parallel, allowing for the use of both inverters at the same time to create a four-quadrant converter.

The original control system of these industrial converters has been removed and replaced by a custom-made control board system LARA-100 by PERUN [7] as shown in Figure 2. This modification completely preserves the industrial power hardware of the original converter and opens up the possibility to deploy custom control software. LARA-100 sets of boards include a motherboard that hosts a Texas Instruments C2000 controller [8] (TMS320F28335 DSP on a DIMM card) and allows for the connection of several extension boards. These include a general-purpose input/output board with various analog and digital inputs and outputs, an application board for voltage measurements, an application board with encoder interfaces, and a communication board with CAN, RS-485, JTAG, UART, and USB connectivity. Such a configuration allows one to easily flash the DSP with new code, without having to worry about resource mapping, as almost all pins have a predefined function or sub-circuit connected to them. The final part of this system is PERUN PowerDesk (seen partly in Figure 2), a software tool allowing communication with DSPs and access to many variables in the control code running in the DSP, either for their manipulation or pure visualization.

Finally, the PETS connection panel also hosts two 25-pin D-Sub extension connectors toward a custom-made PETS Remote board (Figure 5), a 15-pin D-Sub connection for an external incremental encoder, and an RJ connector to access the dc power supply programming and simulation mode. Needless to say, various protection equipment is installed inside the PETS and not discussed here for the sake of space.

Teaching Philosophy

The PETS was developed, having in mind a certain way to bring concepts of digital control for power electronics closer to students while presenting them with software toolchains that are now widely accepted in the industry. To achieve learning objectives, a four-step approach is followed as illustrated in Figure 3, and elaborated in more detail in incoming sections. For a presented new concept or theoretical considerations, operating principles, average or small-signal modeling, tuning (if any), and some variations and evolution of the concept are covered in lectures. This is also supported by dedicated PLECS [9] models, run during lectures, allowing for the interactive change of operating conditions, parameters, and discussion with students.

Laboratory exercises complete the remaining three steps and are highly practical. Students themselves would first implement models and validate them in offline simulations using PLECS. In the subsequent step, they would perform real-time simulations on a digital twin of PETS. Namely, they would develop and deploy control algorithms on the same TI C2000 controller installed on the PETS, and perform real-time hardware-in-the-loop (RT-HIL) simulations with the PETS power hardware and surrounding application modeled and emulated on the RT Box [9]. This allows for safe testing and debugging of the control software, without the risk of damage to any physical elements. Once validated, the control algorithm (DSP software) is transferred to the PETS and validated experimentally under relevant operating conditions, normally without any change of control software developed in the previous step.

Theoretical Backgrounds

With the aim of teaching digital control in power electronics and with the limited time available during the semester, one has to narrow down the selection of relevant concepts and technologies. In a top-down approach, specific applications are considered in order to understand the application requirements and define the control objectives. It is also observed that students are much more engaged when the control problem can be associated with an application that they understand, can visualize, and relate to. This is typically followed by the development of adequate models describing the plants associated with the object to be controlled, and by the identification of state variables and means to influence them. Then, suitable power electronics converter topologies are selected, together with adequate PWM principles. Synthesis of the control diagrams to achieve control objectives is performed together with the selection and tuning of the controllers. Finally, digital signal processing considerations, such as discretization, sampling, and delays are taken into account.

Many concepts are typically new to students and require illustrative explanations that are proven to be the best when attached to an actual application, e.g., why a PI regulator used for parking an expensive car into a garage should not have an overshoot in its response

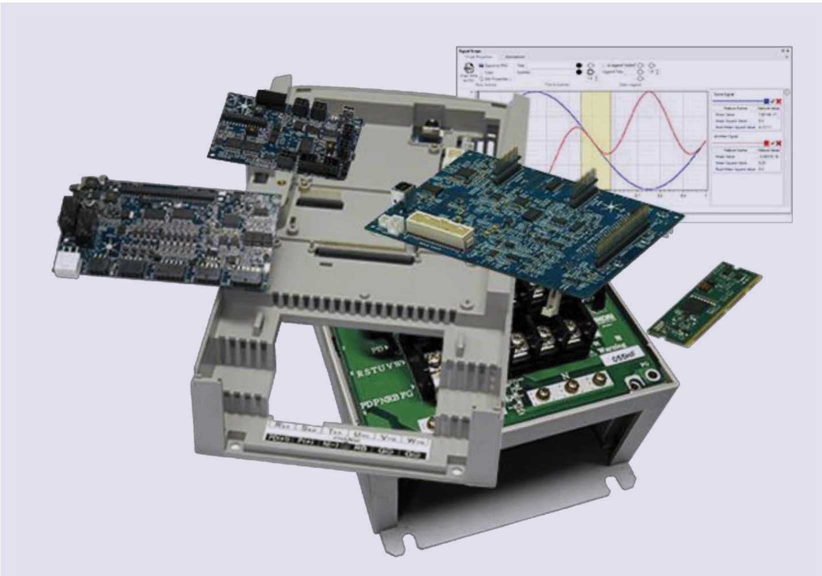

FIG 2 LARA-100 system by PERUN, consisting of a Texas Instruments C2000 DSP and application boards, interfaced with one another and with the power hardware through a motherboard, including communication with a host PC [7].

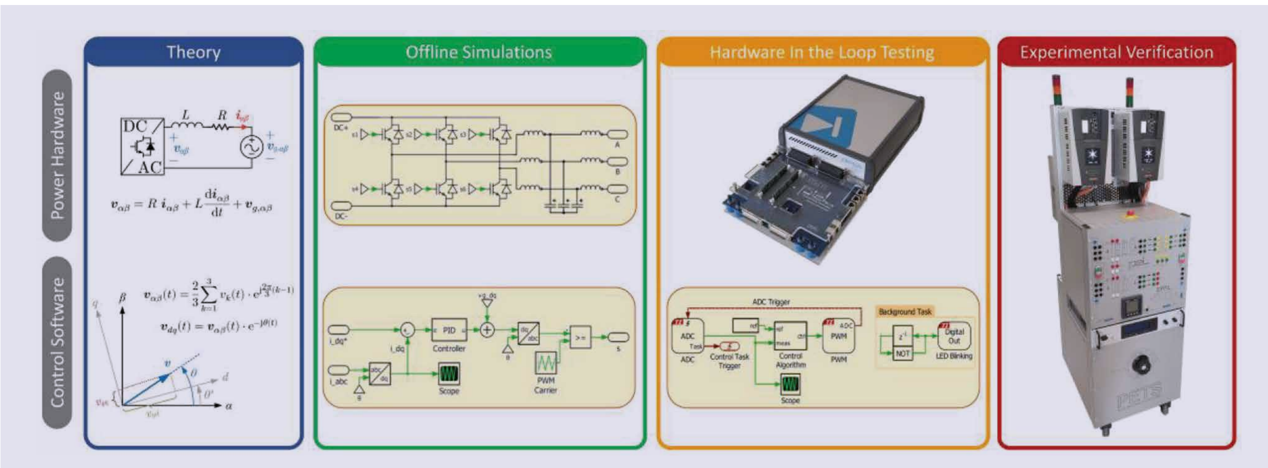

FIG 3 Teaching philosophy executed in four steps: theory, offline simulations, real-time software testing, and experimental validation.

to a desired distance forward command. Note that in the case of a cheaper car, this is desired also. These kinds of anecdotal additions have a surprisingly strong impact on learning. Following a presentation of the new theoretical concepts, students would move to the practical implementation and step-by-step validation, starting with modeling and offline simulations.

Offline Simulations

Although there are many excellent offline simulations software, we have been primarily using PLECS for many years now. The main reasons are the portability of the standalone version and the availability of free student licenses valid for 12 months, sufficient to cover two semesters of teaching. While there is a PLECS toolbox version of MATLAB [10], it is not easy to manage this with many international and exchange master students having different access rights to MATLAB from their home universities.

The value of offline simulations in power electronics does not require justification, as it has become a part of the power electronics development process a long time ago. As we use it to support learnings in the domain of digital control, the fact that PLECS uses ideal switches for the simulation of power semiconductor devices does not represent a problem of any kind. The development of offline simulation models and simulation runs allows students to gather a better understanding of new concepts and to vary almost all parameters that are at their disposal. There is a learning curve related to the type of simulations (variable or fixed time-step), solver selection, accuracy ranges, etc., but many of these are well explained in manuals and quickly understood. Offline simulations always produce some results, so care is taken to formulate exercises in a way that there are quantifiable results to be reported, expecting critical thinking and analysis to be done by students. Simulating a 1 kW rated converter should not produce 1 MW of switching losses, even though it is not a problem to achieve this in offline simulations performed by students.

Care is taken to clearly distinguish what is software and what is hardware in the simulation environment, what

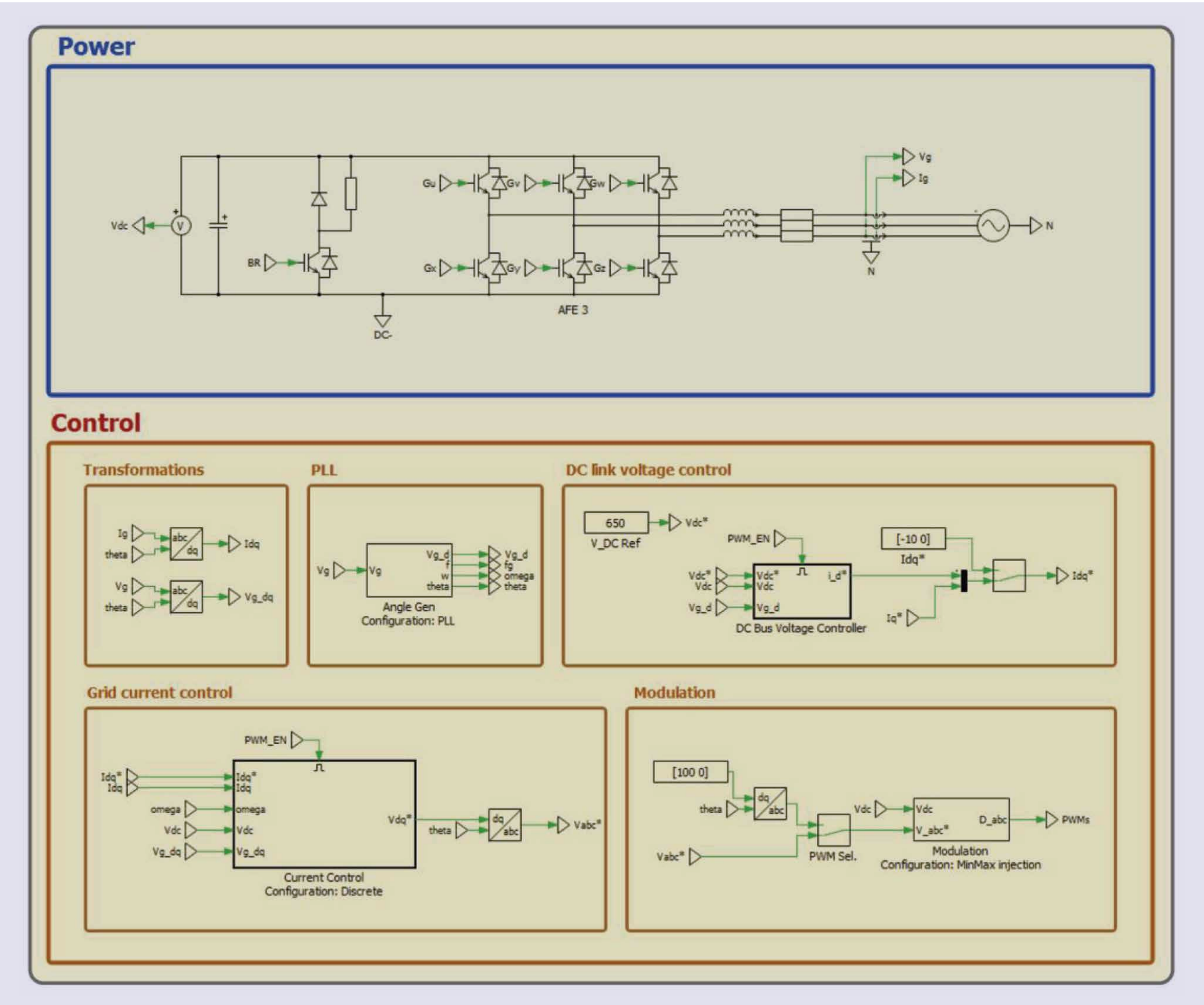

FIG 4 An example of the PLECS model for offline simulations.

simplifications are acceptable, and what abstractions are justifiable. In most cases, control algorithms are implemented using graphical signal flow and representation, as shown in Figure 4, even though C-scripting is possible and used occasionally. As we cannot expect every student to be proficient in programming in C language, a graphical signal flow provides an easy way to track the control logic and signal routing. This becomes even more important in the next step of the process when control principles must be transferred to control software that can run on a DSP.

Real-Time Hardware-in-the-Loop Validation

The use of digital twins (popular terms nowadays) or RT-HIL systems in industrial research and development has been an accepted practice for many years already [11]. Various vendors (e.g., OPAL-RT, RTDS, Typhoon HIL, dSPACE, Plexim,…) and systems are available on the market, offering different performances in terms of the input/output signals that can be managed, the number of state variables that can be simulated, or the minimum step size associated with the time needed to update real-time models. There are various terms and names associated with RT-HIL systems, depending on what is real and what is actually emulated in the test set-up.

In our case, both the application and the PETS power hardware are modeled and emulated on the RT Box from Plexim. Control software is deployed on a real TI DSP, which is interfaced to the RT Box through a dedicated PETS HIL board, as shown in Figure 5(a). The developed RT-HIL system is a digital twin of the real setup, made as an exact replica of the actual PETS, cost-optimized to include all of the LARA-100 features and support a safe environment for the control software development and testing. In summary, in our RT-HIL system, the controller and control software are real, while everything else is emulated in real-time.

What is real-time? The answer to this will greatly depend on the actual dynamics of the system to be emulated. A few milliseconds to update all state variables of the models may be perfectly fine for power system simulations, but it is not fast enough for the majority of modern power electronics applications involving high switching frequencies. Typically, power electronics simulators aim to achieve step sizes near or around 1µs or a few µs, depending on many factors that are beyond the scope of this article. With the PETS, our switching frequencies never exceed 10 kHz due to power hardware limitations, and the RT Box has sufficient computational power to execute all models below 5 µs.

Another important detail is how the control software is generated. To avoid reliance on students' knowledge of programming in C language, and considering that we are not generally interested in the quality of their code but rather in its performance, the automatic code generation of PLECS is used. The PLECS CODER feature is used to generate the code for two targets: the control software for the TI DSP and the real-time model code executed on the RT Box. Clearly, an effort is needed from our side to explain the architecture of the DSP, its various peripheral units, and the structure of interrupts, as well as from students to gather understanding and confidence to start testing. External signals can be interfaced with DSP software by means of a PETS Remote board, shown in Figure 5(b). Its purpose is mainly to provide external inputs and outputs to the DSP control software, both for the PETS and PETS RT-HIL system. This is implemented mainly to engage in better learning of DSP peripherals.

There is a clear difference between simulation models for offline and RT-HIL simulations, and the discussion on those is beyond the scope of this article. For those interested in working with the RT Box, details and peculiarities can be found in [12]. While students would develop offline models themselves, we would provide them with RT Box models, considering that the PETS configuration is known and signal exchange between the RT Box and DSPs is fixed. As an example, the offline simulation model from Figure 4

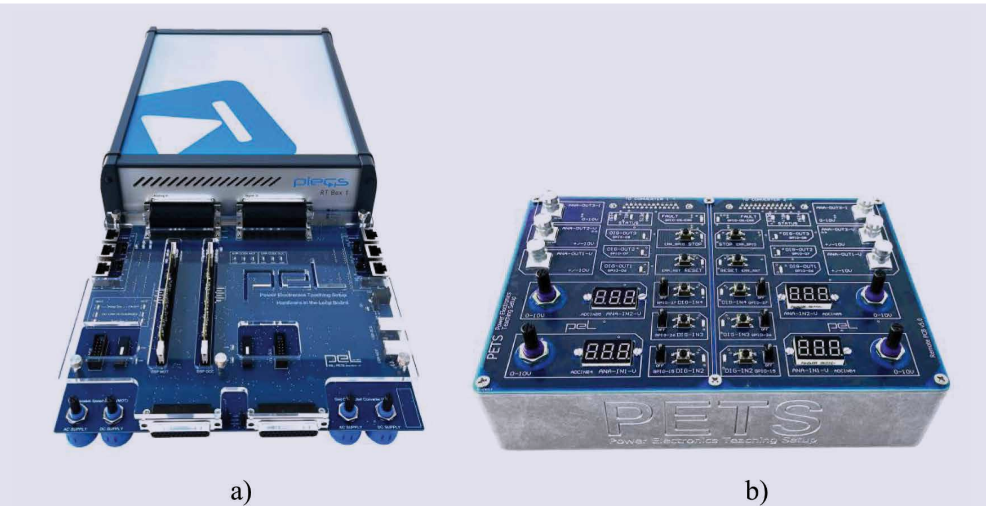

FIG 5 (a) The PETS HIL board developed to support control software development and testing, together with the RT Box creates the exact digital twin of the PETS. (b) The PETS Remote board.

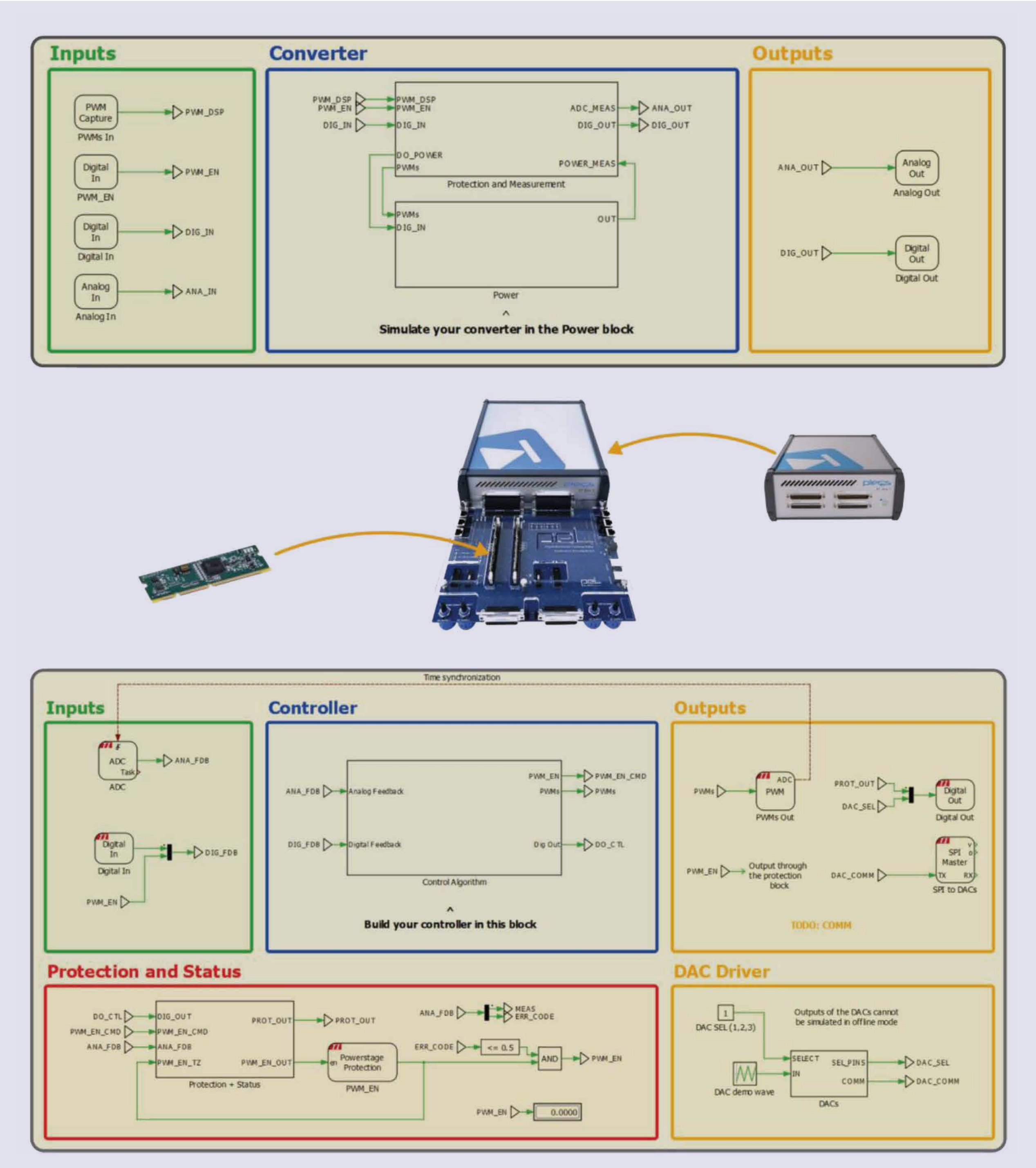

FIG 6 The PLECS model used for RT-HIL simulations and the DSP code generation.

is expanded to the RT-HIL model and shown in Figure 6. An obvious difference is that the RT-HIL model sends and receives signals from the "outside" of the RT Box, namely from the DSP controller. Thus PWM signals from the DSP are directly sampled by the fast digital inputs of the RT Box and applied to the plant models, while analog signals, typically voltages and currents, are generated at the analog outputs of the RT Box and sampled by the ADC inputs of DSP. Nevertheless, the modeling and programming are done in the same environment, accelerating the learning curve for the students.

Experimental Validation on the PETS

Following the successful development and validation of the control software on the PTS RT-HIL system, a final experimental validation is done using the PETS hardware from

Table 1. System-level parameters used for the example presented in the article.

Parameter	Value	Parameter	Value
AC Filter Grid-Side Inductance	3.5 mH	AC Grid Rated Voltage	400 V (RMS)
AC Filter Converter-Side Inductance	3.5 mH	AC Grid Rated Frequency	50 Hz
AC Filter Capacitance	6.8 μF	DC link Capacitance	700 μF
Switching Frequency	10 kHz	DC link Rated Voltage	650 V

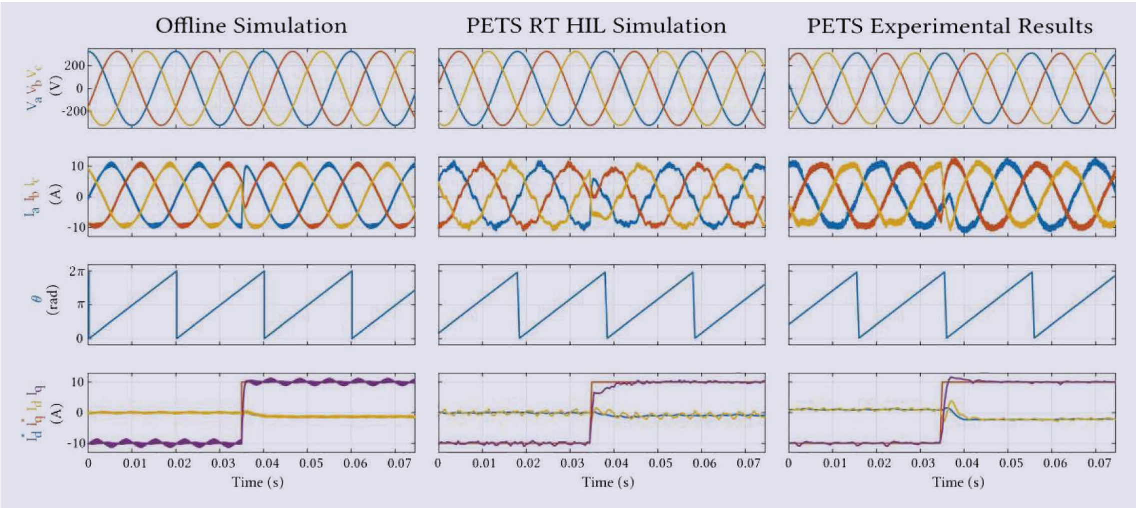

FIG 7 Exemplary results from offline simulations (left), the PETS RT-HIL simulations (middle), and the PETS experimental results (right). From top to bottom: grid voltages, grid currents, and grid voltage angle estimated by the PLL, Id, and Iq current references and actual grid currents after being transformed into a rotational reference frame.

Figure 1. Connected to the surrounding laboratory infrastructure and with the front panel wired in the relevant configuration, the validated DSP code can be loaded and commissioning sequences can begin.

For illustration purposes, an example is presented here, considering the case of a three-phase grid-connected converter. Control is implemented in the d-q frame, utilizing PI regulators for both voltage and current control (where various tunning approaches can be exercized), with a PLL providing the grid voltage angle and frequency. The model and control system are already shown in Figure 6, while the parameters are listed in Table 1. Results are shown in Figure 7, which clearly illustrates the high fidelity of simulations (both offline and real-time) as well as an excellent agreement with experimentally measured data. All results in Figure 7 are gathered using the PLECS in external mode, hence accessing the DSP software during real-time simulation or experimental investigation.

Concluding Remarks

Developing the PETS was a large effort on our side, and it took a few iterations, prototypes, and a lot of testing to define the final concept. As of today, 22 units of PETS RT-HIL systems and 22 units of PETSs have been manufactured and rolled in use at EPFL, as seen in Figure 8. Initial deployment was restricted to semester projects, master theses, and doctoral courses, in order to gather feedback from the early users, and develop supporting material. Clearly, PETS offers a limited number of configurations, but those available are judged sufficient to represent a large number of applications. With the focus being on digital control, the PETS ecosystem merely provides support and opportunities for students to push their control development through all relevant phases, as described in the preceding parts of the article. In this way, we emulate practices that are already followed by the industry and expose students to modern design tools. Limits to what control schemes can be deployed are defined purely by the creativity of students and the computational capabilities of the used DSPs.

In conclusion, teaching power electronics is a challenging task, that requires a deep understanding of both theoretical and practical concepts. Our aim is to transfer knowledge and skills to the next generation of engineers, and the best way to boost engagement, improve motivation, and stimulate curiosity and inventiveness, is just to have the help of the right PETS.

Acknowledgment

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FIG 8 Developed PETS units eagerly waiting for conversion problems.

development of the PETS through the Discovery Learning Laboratories program. The cat is real. His name is Lemon. Good boy.

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