Digital Real-Time Simulation Advancing Education and Training on Power and Energy Systems

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Abstract—**Tackling the challenges of the energy transition requires a skilled workforce and advanced educational and training tools. During the previous years, a relatively large number of institutions have acquired Digital Real-Time Simulators, in both academia and industry. However, this is mainly used for practical studies and research, while the use of real-time Hardware-In-the-Loop (HIL) simulation for education and training is rather limited at the moment. In this framework, this work investigates the potential of using HIL simulation for education and training purposes on power and energy topics in both academia and industry. Selected reference experiences of the Task Force members are presented along with learners' feedback to substantiate the effectiveness of the approaches. Particular attention is given to training and education at industrial level, which has not been adequately addressed in the literature, so far. The use of remote laboratories and safety concerns are also addressed.**

Index Terms— **Digital real-time simulation, Education, Energy, Hardware-in-the-loop, Industry, Power system, Training**

I. Introduction

Modern power and energy systems are characterized by the decentralization of energy generation, the integration of Distributed Energy Resources (DERs), the interconnection of different energy carriers, new market models, and the wide use of Information and Communication Technologies (ICT) in all areas. To respond to the emerging industrial needs in a complex multi-domain environment, new skills and expertise are necessary across different fields [1][2][3]. The role of education and training is of great importance to create a new generation of professionals and innovators who will address the current and future challenges. Luckily, recent technological advancements can revolutionize education by providing a plethora of new tools and possibilities, easier access to material and specialised knowledge. E-learning receives unprecedented attention with the roll-out of Massive Open Online Courses (MOOCs), webinars, and advanced tools such as interactive notebooks. New ways of laboratory education are emerging, such as remote (distance) labs, real-time simulation, and augmented/virtual reality. Particularly real-time simulation techniques can enhance the laboratory education experience, due to the increased capabilities that they offer such as the inclusion of actual power or control components in the simulated scenario. Meanwhile, active learning, problem-based learning, and experiential learning, among others, are increasingly gaining interest, while the importance of addressing different skill levels (e.g., according to Bloom's taxonomy) has been recognized [1].

Real-time Hardware-In-the-Loop (HIL) simulation has proven its effectiveness in testing and validation of power system apparatus and controls [4]. In fact, Controller-Hardware-In-the-Loop (CHIL) setups prove an effective solution to incorporate actual control devices in the simulation environment, while the more advanced Power-Hardware-In-the-Loop (PHIL) technique further expands the simulation fidelity by integrating actual power equipment. CHIL, but in some cases also PHIL simulation, has been used for education and training [5]-[16], including applications in the power and energy sector. Its distinct advantages for education/training include the similarity with a real system, flexibility of modeling, hands-on experience of using hardware devices, real-time operations, safety, etc.

The use of real-time and HIL simulation has become quite popular during the last few years. Currently, a significant number of academic, research, and industrial institutions (e.g., grid operators, converter manufacturers, relay manufacturers) operate Digital Real-Time Simulators (DRTS) [17] for research, development and testing purposes. However, the use of real-time and HIL simulation for education and training is still limited and a systematic analysis of the HIL benefits for education, along with reference teaching scenarios is missing. Moreover, very limited information on the use of HIL for industrial personnel training is available, while the use of remote HIL has not been comprehensively explored. In this framework, this work sheds light on the potential of using HIL simulation for educational/training purposes on power/energy topics in both academia and industry, based on the experiences of the members of the IEEE PES Task Force (TF) on "Real-Time Simulation of Power and Energy Systems" and the IEEE PES TF on "Innovative Teaching Methods for Modern Power and Energy Systems" [1]. Particularly, the capability of real-time and HIL simulation to provide new perspectives within education on crucial topics of modern power and energy systems is showcased. The topics under discussion have been motivated by recent IEEE TF technical reports on power system and microgrid dynamics [18][19], as well as power electronics applications and DER integration [20][21][22]. Moreover, machines and drives for transportation electrification are discussed. The discussions have particularly been built based on the evolution from real-time simulation to CHIL and PHIL testing, i.e. similar to the Technology Readiness Levels (TRL) upscaling HIL testing chain [23]. Training of professionals and system operators, particularly on HVDC and cyber-resilience aspects, as well as the realization of remote laboratories for educational purposes are discussed and reinforce the contribution of the paper.

The paper is structured as follows. Section II focuses on real-time and CHIL simulation for modern power system dynamics education. Section III investigates the application of CHIL simulation for Power Electronics (PE) education, while Sections IV and V focus on PHIL-based education for DERs and machines/drives in transportation electrification, respectively. Sections VI and VII discuss the applicability of HIL simulation for power system operator professionals and cyber-physical energy systems professionals, respectively, and Section VIII highlights the applicability of HIL simulation for remote laboratory education. Section IX discusses real-time simulation in virtual laboratories and Section X briefly refers to laboratory safety concerns. Section XI concludes this work. The presentation includes educational needs, reference teaching scenarios, as well as feedback and challenges.

II. Real-Time and CHIL Simulation for Modern Power System Dynamics Education

A. Educational needs and advantages of real-time and HIL simulation

Power system dynamics have become one of the most challenging problems to understand because of the wide penetration of power electronic converters interfacing DERs, FACTS, HVDC connections, etc. This is reflected in the revisited classification of power system stability that focuses on the effect of converter interfaced components in rotor, frequency, and voltage stability and introduces the converter-driven stability class [18][24]. Converter-driven stability refers to phenomena of instability (short or long-term) that originate from operations of power electronic converters. The PE converter response is dictated by its control [25], contrary to synchronous generators, therefore the control techniques of inverter-interfaced DERs play a crucial role in the stability of modern power systems. PE converters decouple the physical inertia of rotating machines from the power system, thus decreasing the overall inertia of the system. Approaches to include virtual inertia or advanced frequency control properties to the inverter-interfaced DERs [26] have been proposed. It is clear that modelling the inverter-interfaced DERs and power system dynamics as faithfully as possible is crucial to understand stability issues of modern power systems. Suitable education/training is needed to effectively understand and familiarize with these issues on academic and industrial levels by providing training and hands-on experience.

One of the key technologies that enable this type of analysis is modern digital real-time simulation that allows power system design, operation, prototyping, and testing. Real-time simulation can also be used effectively for teaching and training, tackling the problem of the required skill gaps. Dynamic simulation of power systems necessitates solving a large number of algebraic and differential equations, typically using numerical analysis. The DRTS uses parallel computing to solve these equations in real-time. In this way, the results are made available to the user/operator almost in real time, as in the actual power system [11][27]. Therefore, interactive real-time simulation is a valuable educational tool that allows students to experience complex adaptive modern power system issues.

By incorporating hardware controllers in the real-time simulation, namely performing CHIL simulation, the student obtains additional benefits, such as the experience of using actual controllers and the more realistic behaviour. This is particularly interesting for modern power system dynamics, where the interactions of inverter controllers give rise to converter driven stability issues.

B. Reference teaching scenarios

Real-time simulation is valuable for education, as the events under study evolve in real-time, and this direct interaction can attract the attention of students. As an example on the educational application of a real-time simulation of power system dynamics, the transient stability of grid-connected converters [28] was presented to postgraduate students in the "Modern Energy Conversion Systems" course in the Institute of Aviation Engineering and Technology in Egypt. The real-time simulation results were compared to those obtained in the conventional Matlab/Simulink environment for validation purposes. Thus, the effectiveness of the control techniques was tested in real-time. In this educational application the students evaluated each other through online peer assessment.

CHIL simulation is applied in the graduate-level "Smart Grid Technologies" course offered at Georgia Southern University, USA. The students are taught microgrid control and dynamics, being exposed to various pilot North American microgrids employed in both teaching and research. Part of the Illinois Institute of Technology microgrid, including renewables, battery systems, and combined heat and power (CHP), is tested via CHIL simulation. The students are engaged with the frequency control response to load changes in islanded microgrid (with low inertia) mode, benefitting from experiential learning of microgrid stability. The frequency response of one of the tests has been plotted on an oscilloscope through the CHIL platform analog outputs (AOs) to display to students the control integration happening inside CHIL simulations. Thanks to the flexibility of the real-time simulation, the students can see how the control parameters impact microgrid dynamics and stability. Two sets of controller parameters were applied to compare the impact on the frequency response, when two DERs are supplying a load in an islanded microgrid. Fig. 1 depicts the identical frequency of the two DERs during an increase of the active load. CHIL testing was applied, where the control algorithm was running on a Xilinx platform for Field-Programmable Gate Arrays (FPGAs) interacting with the DRTS.

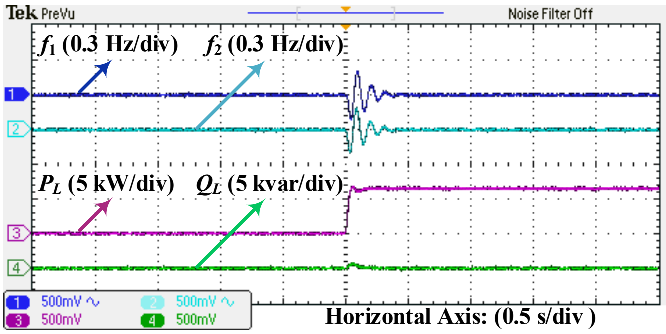

Fig. 1. CHIL simulation of the microgrid frequency response: increase in the load active power

C. Feedback, Challenges and Opportunities

In the real time simulation, the students received instruction on various topologies and faults to determine the most crucial stability analysis and control metrics. 90% of the students reported that they were very satisfied with the suggested methods, appreciating the immersive experience, simplicity, and obviousness. Moreover, students performed many group projects, such as modeling small test systems in the time domain to understand voltage and transient stability with and without faults to help determine the duration allowed to perform preventive actions. Concerning CHIL simulation, the challenges included the complexity of the developed laboratory setup, impacting the active learning strategies that the students are encouraged to employ.

III. CHIL Simulation for Power Electronics Education

A. Educational needs and advantages of HIL simulation

As explained in the previous section, a gap in skills and competence can be identified in the behavior of PEs and their potential impact on system behavior. From a PE perspective, the design process does not stop where the converter ends, therefore awareness of converter system interactions is critical. It is important to address interconnection challenges of inverter-interfaced DERs, understanding of power systems with large proportions of them, their interactions within a system and the development of associated control concepts. Such engineering skills should be translated to power system control rooms, field engineering and eventually, power engineering graduates.

Rapid developments in DRTS and CHIL experimentation with the transition from custom hardware designs to off-the-shelf components, greater processing capacity, decreasing costs, more compact design, faster and simpler development cycles and greater available support and expertise, make CHIL a critical component of a modern power engineering education curriculum and a key step in addressing knowledge gaps. The faster implementation and experimentation cycles achieved through CHIL mean that broader topics can be covered, while accommodating material aimed at continuous education and practitioners. Moreover, implementation cost of laboratory setups is reduced compared to the costs of full converter, high-voltage/high-power supplies and the associated health & safety requirements. Converters can be tested for multiple critical grid faults and in scenarios that cannot be practically demonstrated in the field, while black box modelling approaches and industrial solutions can be directly used in the educational process.

B. Reference teaching scenarios

Common education examples for PEs in a laboratory environment focus on the converters e.g., validation of operating principles, pulse width modulation, low-level control etc. More recent examples incorporate controller design typically through offline simulations, with subsequent code generation to a real controller target and control of low-power laboratory prototypes, specifically designed for educational purposes. These approaches, which constitute Level 1 of a modern PE education teaching scenario, do not provide all the skills necessary for a comprehensive PE education. Using CHIL, PE learning and teaching objectives can be scaffolded from undergraduate to postgraduate education.

Different approaches to PE education are presented below. These are applied at the graduate level course "Real-time Simulations" of the University of New South Wales in Australia.

- **Level 1: Using offline simulations** of PE converters and low-power educational prototypes to demonstrate first principles and operation of PEs. Such an approach is typically suited to undergraduate courses (e.g., third year of a four-year degree), and can be supplemented with low-cost hardware, simple implementation basic laboratory skills, and a well-prescribed but limited hands-on experience for the students.
- **Level 2a: Development of PE control functions using simulated converters in real-time simulation as a CHIL application.** This approach, aimed at years 4/5 of an undergraduate program provides hands-on experience with the development of controllers for PEs in a well-controlled environment and in a structured manner. The limited risk of CHIL and the ability to scaffold from simple low-cost controllers (e.g., Raspberry Pi, Arduino etc) to full-scale DSP and FPGAs provide a complete educational experience for the students. Relatively low cost and a lower barrier to entry for institutions that seek a scalable and, in many cases, ready-to-deploy solution allows for extension of Level 1 skills to practical problems and demonstrations.
- **Level 2b: Taking advantage of Rapid Control Prototyping (RCP)** platforms for the development and deployment of control functions, experimentation can be extended to include converter setups. This allows students to develop experience with hardware and practical development skills without the need to fully implement software/hardware or custom code e.g., PWM implementations in an FPGA, IOs as these can be pre-developed and packaged. As this approach extends hardware requirements and the need for a power converter, it is typically suited to master's level programs or project-oriented learning.
- **Level 3: Refined controller / converter implementation** can be deployed, when practically possible, as part of a

master's level course or a postgraduate project in full hardware allowing students to further develop their laboratory skills. This also increases lab requirements for safety, hardware availability, supervision and eventually cost.

A summary of these approaches for PE education is provided in Table I. It lists a qualitative comparison across eight key criteria, highlighting their relative strengths and limitations. By examining these approaches across multiple dimensions, educators can make informed decisions about integrating CHIL and real-time simulation into their curriculum aiming to optimize learning outcomes and resource allocation

TABLE I: SUMMARY OF APPROACHES IN PE ENGINEERING EDUCATION

	Simulation (Level 1)	**CHIL (Level 2a)**	**RCP (Level 2b)**	**Full Setup (Level 3)**
Modularity	Moderate	High	High	Low
Flexibility / versatility	Moderate	High	High	Low
Hardware costs	None	Moderate	Moderate	High
Development time	Low	Moderate	Moderate	High
Safety Requirements	None	Low	Moderate	High
Interaction	Low	High	High	High
Observation	Low	High	High	High
Engineering Skills Development	Low	High	High	High

To meet the requirements of Level 2a and Level 2b, CHIL supporting facilities are required. Such facilities, per simulation / experimentation bench require, at minimum:

- One DRTS capable of simulating PE converters at high fidelity. This allows for multiple converters to be simulated (either separately or simultaneously) from a single setup.
- One or preferably, multiple control hardware platforms (e.g., Arduino, Raspberry Pi, DSPs, FPGAs). Low-cost controllers can also be distributed on a per-student basis, while development can take place outside the laboratory, optimising the utilisation of the laboratory. Addressing Level 2b requirements, one RCP development kit can also be included in each bench.
- One PC including all supporting software for real-time simulation and programming of the controllers (e.g. DSPs). Remote access can also help extend the laboratory hours by allowing students to develop and work on the setup without requiring their physical presence in the laboratory.
- Oscilloscope and measurement probes
- Cables and interfaces between controllers and DRTS
- Optionally, a PE converter can be included for demonstration purposes – particularly for Level 2b implementations. Such converters can be common across multiple setups.

Fig. 2 shows possible implementations for incorporating both Level 2 options in a single laboratory bench.

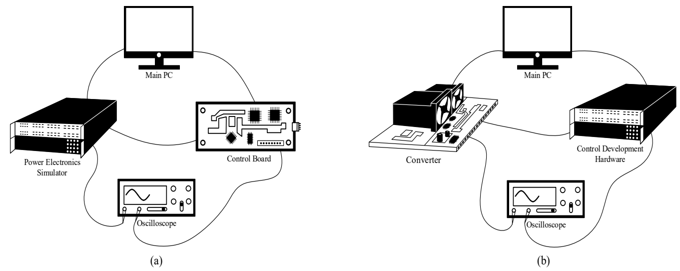

Fig. 2. Generic examples for real-time simulation in PE education: (a) Controller HIL (CHIL) and (b) Rapid Control Prototyping (RCP) setup.

Different teaching sequences can be used depending on the focus of each course, the learning outcomes and level of students in order to create a personalised learning experience. Some common examples include teaching with a focus on control skills for PEs or focus on development and deployment of real-time simulation solutions for PEs. Such examples are elaborated further.

- **PE control and integration skills**: From introducing basic control concepts in PE, students can be provided with the specific requirements for an application based on which they can further develop their control implementations. For example, Fig. 3. shows the response of a converter to a step-change in the active/reactive power set-point from 0/0 pu to 0.5/0.5 pu. Different control parameters are applied and their impact is measured. Multiple cases and extreme scenarios can be safely tested based on CHIL configurations. Such cases can include common or uncommon scenarios, such as microgrids, DER integration [29] and grid-forming inverter-interfaced DERs. The students can develop and validate multiple internal current and voltage controllers, high-level droop and inertia responses, study the impact of phase-locked loops (PLLs) on PE and test grid disturbances, voltage ride-through compliance or islanding detection and power sharing. The control functions are developed, converted, validated and tested across many possible scenarios.
- **PE real-time simulation skills**: In order to develop real-time simulation skills for students, educators can choose to introduce critical concepts of real-time simulation, such as the timestep and its importance for PE modelling, representation of switching devices, modelling domains (e.g. Real-time EMT vs EMT vs RMS) and model types (Type 1 to Type 8 from physics based component level models to RMS type simulations) [30]. In this way, students can develop skills in selecting appropriate modelling methods and techniques before applying them to specific applications, e.g., HVDC transmission, renewable energy integration etc.
- **Integration of industrial controllers**: Even with the minimum hardware setup, introduced earlier, it is possible to extend laboratory setups to incorporate commercial hardware or even industrial controllers (e.g. converter controllers for photovoltaic systems, plant controllers of wind-farms, HVDC control replicas etc.) usually in

partnership with industry that can also utilise the laboratory for training and demonstration purposes.

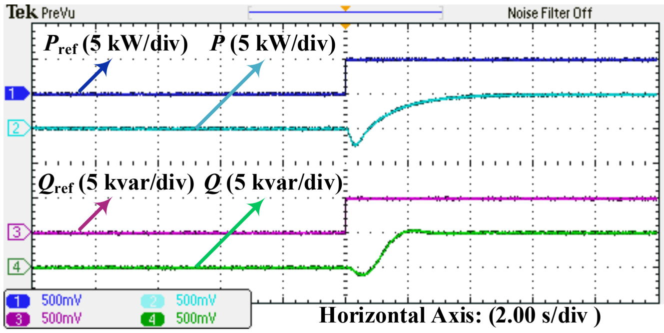

Fig. 3. Example of a CHIL simulation demonstrating the impact of controller design and parameter selection in the response (active and reactive power) of a grid-following converter.

C. Feedback, Challenges and Opportunities

From a student perspective, hands-on experimentation with real-time and CHIL simulation provides a new educational experience that integrates skills from the whole engineering curriculum. Specifically, students commented positively on the practical aspects of the course and the hands-on approach, noting that they were able to effectively apply their knowledge in practice. Moreover, they appreciated the increased interaction between students and instructors. Both aspects are critical in creating a supportive and engaging learning environment across all levels.

While considering all the positives, integration of CHIL and real-time simulation in a PE teaching plan comes with its own challenges. A minimum set of competencies before the students can work in this environment is required, which may create challenges for scaling beyond a certain number of students. Scaffolding of knowledge is also critical and appropriate checkpoints throughout the teaching session should be included. This aspect should also be considered in the design of formative and summative assessment tasks that need to balance skills development and competencies in the topics of the course. A hands-on experience for students needs to consider a balance between access to facilities and availability of equipment. Moreover, economic aspects need to be considered, as a substantial investment is required for establishing a CHIL/real-time simulation laboratory for educational purposes, despite a generally lower cost compared to a full converter setup.

IV. PHIL Simulation for Education on DER Integration into Power Systems

A. Educational needs and advantages of HIL simulation

On top of the setups discussed in the previous sections, PHIL simulation involves the connection of power hardware equipment to the DRTS, using a suitable power interface (power amplifier and sensor). Although CHIL simulation has been used several times for education, the use of PHIL simulation has been less applied, as this is a more complex and challenging method [5][6]. Power engineering students can greatly benefit from education/training using PHIL simulation, as it combines the advantages of simulation and hands-on experimentation with actual power hardware. In this way, the students can interact with hardware power devices, such as PV inverters, motor-generators etc., when connected to a broader real-time simulated power system, where a multitude of scenarios can be examined.

B. Reference teaching scenarios

In the graduate-level "Advanced Power Systems", "Smart Grid Technologies", and "Converters Control Techniques" courses delivered at Georgia Southern University, USA, the students are taught the integration of several DERs into different types of grids. The PHIL setup allows students/trainees to take advantage of experiential learning. As explained in Section II, the students are taught the DER integration into microgrids considering different conditions, using CHIL simulation. Here, PHIL-simulation-based testing is applied, providing valuable hands-on experience of using actual power equipment to the students. For example, Fig. 4 shows the PHIL results associated with an increase in active power of inverter-based DER in low-inertia grids (active power and frequency of the two DER, P_1 and P_2, as well as f_1 and f_2, respectively). Different control parameters are used leading to different responses. Moreover, the students/trainees are also exposed to DERs' capabilities in modern power and energy systems, such as Fault-Ride-Through (FRT), voltage and reactive power control etc. The PHIL setup is shown in Fig. 5.

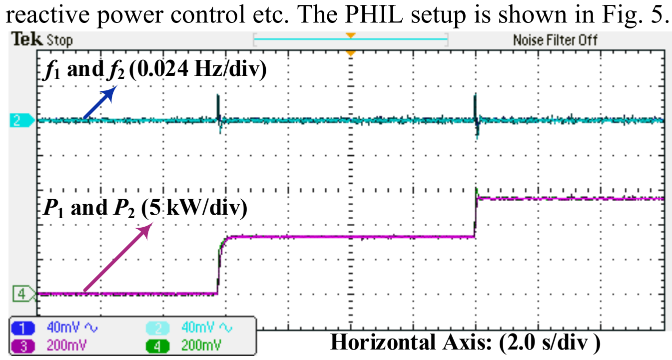

Fig. 4. PHIL simulation results of inverter-based DER in low-inertia grid: active power increase

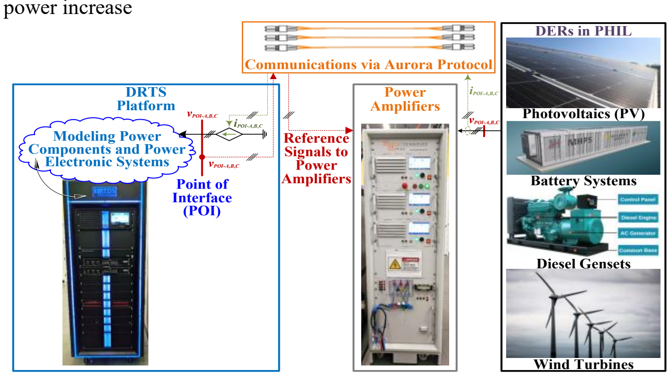

Fig. 5. PHIL setup for DER integration

C. Feedback, Challenges, and Opportunities

The students' feedback has been encouraging. They have rated the instructor's teaching strategy as very interactive, having the students very actively involved. The instructor has employed their suggestions on challenges to improve his experiential learning's impacts. The primary reasoning behind the challenges the students faced included having many components to be taken care of during the experiments. The flexibility in simulating different aspects of DER integration into power systems, which is not easily feasible in traditional education on power systems, is among the unique opportunities.

V. PHIL Simulation for Machines and Drives Education in Transportation Electrification

A. Educational needs and advantages of HIL simulation

The recognition of the role of Power Electronics, Machines and Drives (PEMD) in the decarbonization of transport sectors such as automotive, aviation, rail and marine has brought upon a strategic shift in roadmaps of core industries and their supply chains catering the sectors, working towards capitalizing on new and niche markets. This shift in strategic roadmaps has brought in the need for new skills, where the industries are subject to two options to support their growing ambition: (i) to hire new employees with new skills required, or (ii) to reskill their existing staff.

Skills and competence gaps identified may vary from the fundamentals of PE and electrical machines to advanced knowledge of their control and applications. In the context of supporting the electrification of transportation through novel PEMD solutions, the appreciation for modelling systems that are fit for purpose is important, while understanding the trade-offs and assumptions necessary to carry out engineering decisions. Real-time simulation and HIL are essential tools for realizing the ambitions of electrification of transportation as many novel technologies (e.g. system plants) are currently in the conceptual design phase and have not yet been manufactured. Such an environment provides the flexible system emulation capability required to accelerate the development of these novel technologies from proof of concept to prototypes and real-world implementations.

Fig. 6. Decarbonization of transport integration: PHIL setup

B. Reference teaching scenarios

A course on “Control of Motor Drives for Transportation Applications” was developed by the University of Strathclyde, UK, for reskilling employees. It assumes that the candidates have fundamental knowledge of PE (including principles of PWM) and principles of operation of electrical machines. The target audience includes employees from sectorial industries. The objective is twofold: (i) to ensure that the practical use of PHIL simulation for industrial applications is highlighted and (ii) to harness the didactical value of PHIL simulation to reinforce the learning process. The laboratory setup comprises a laptop with Matlab/Simulink and instaSPIN, a three-phase two-level full-bridge power converter and a 55 W Brushless DC (BLDC) motor (Fig. 6). The Matlab/Simulink and instaSPIN allow the programming of the full bridge power converter. The incorporation of a DRTS in loopback configuration for emulation of plants (motors) realizes the PHIL setup. The course includes software simulations using Matlab/Simulink as a first approach for understanding the modelling and control of the motor drives, after which each student is provided with a converter and a BLDC motor for pure hardware experiments. The BLDC motor is controlled as a permanent magnet synchronous machine (despite its trapezoidal distribution, the result is approximately valid). To comply with health and safety regulations, the DC voltage in the power converter is limited to 60 Vdc (maximum allowable touch voltage). The students use the interface of instaSPIN for experimenting with the different control loops and parameters. The experiments in pure hardware are limited to steady-state operation and moderate transients, as large transients during experiments could lead to permanent damage of the motor and/or detuning of the current loop. In addition, flux weakening is not demonstrated due to the risk posed by high-speed operation of the motor. For this reason, the PHIL set-up is employed to safely carry out these experiments and to consider the different machines covered in the lectures. Sample results demonstrating speed control of a BLDC motor are presented in Fig. 7. The exercise involved three step changes in speed as input set point changes (Fig. 7a: blue line). Fig. 7 also presents the tracked speed (Fig. 7a: orange line), corresponding PWM (Fig. 7b) and motor currents (Fig. 7c).

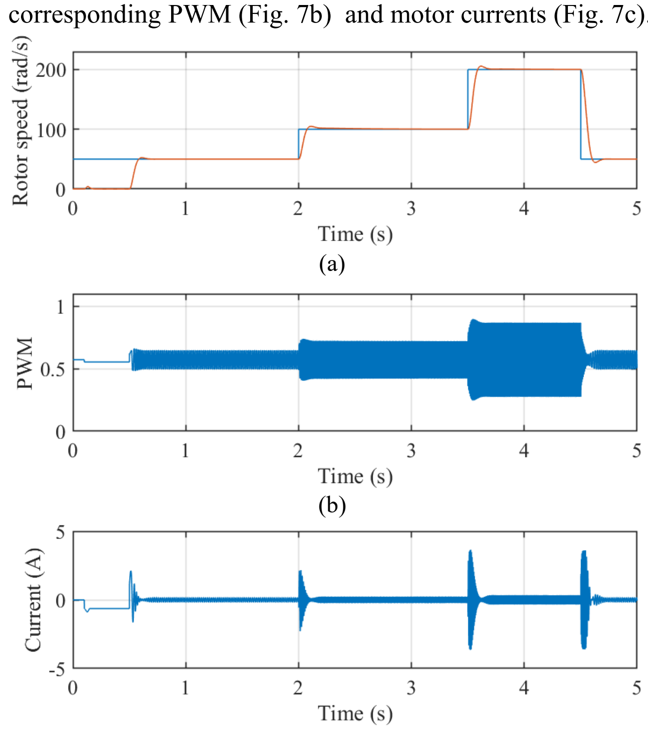

Fig. 7. PHIL for transportation electrification: sample PHIL results for speed control of BLDC motor, (a) rotor speed, (b) PWM output and (c) motor current

C. Feedback, challenges and opportunities

Students were provided with a questionnaire to fill in after completing the course, including generic questions on the teaching approach and specific questions on the didactic value of PHIL. The questionnaire was intended to distinguish between how well the course met the industrial need to learn to effectively use PHIL systems, versus understanding if PHIL had reinforced the learning process by evidencing non-trivial scenarios for evaluating the control and protection actions. The value of utilization of PHIL systems to expand their knowledge was evident from the feedback.

VI. HIL Simulation for Training of Power System Operator Professionals

A. Educational needs and advantages of HIL simulation

The power system transformations discussed in the previous sections, bring their own challenges and require trained operators and technicians for successful implementation. This is especially valid for professionals employed by transmission and distribution system operators, as well as collaborating industries. HIL simulation allows near to real-world conditions to be replicated, ensuring the ability to comprehensively train personnel.

B. Reference teaching scenarios

As part of the derisking exercise for the Caithness-Moray-Shetland (CMS) multi-terminal HVDC link, the first such link in Europe, Replica control and protection cubicles were used. In combination with a DRTS, the Replicas can operate as if connected to the real system. The CMS Replicas are being hosted and operated at the National (UK) HVDC Centre of SSE to provide support to the CMS project by undertaking enhanced system studies, operator training and operational support.

The use of Replicas provides greater availability and flexibility in the delivered training. While the suppliers' focus is on the operation of their product, the HVDC Centre focuses more on the integration with the wider transmission network. The use of Replicas supports the transition from a lecture style delivery to a practical session where the operators can interact with the scheme. Both the effect of changing settings of the HVDC scheme on the network and the effect of network events, such as faults, on the HVDC scheme can be explored with support from the simulation engineers.

The use of Replicas Human-Machine Interfaces (HMIs) means that the operators can have project specific training (Fig. 8). This has allowed them to run through basic and advanced operation of the HVDC link, using the processes that are designed into the scheme. It gave the opportunity for a sign-off process for operating the scheme to be conducted. Moreover, as new staff were introduced into the team, this training was re-run.

Work is currently ongoing to setup a local instance of the Distribution Management System (DMS) of the Control Room, to further enhance the training capabilities. This will enable to transition from purely training on the HVDC operator HMI to a full 'flight simulator' setup for the operators using their everyday setup. Moreover, it will allow for integration with the simulated AC network to expand the scope of the training.

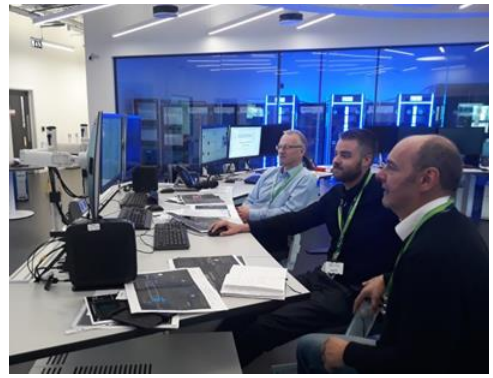

Fig. 8. Control Room Operatives Training on Replica HMIs at National HVDC Centre

Replicas are also used for maintenance at France's Transmission System Operator (RTE), as shown in Fig. 9, to support the preparation of the annual on-site maintenance operations. This preparation includes testing and validation of the upgraded system before field implementation. To perform preparations for maintenance, validation of upgraded control system, fault diagnostics and training of operators, the Maintenance Replica includes a set of control and protection cubicles identical to the original cubicles in the converter substations with the same interfaces, including any redundant equipment implemented in the converter cubicles.

In addition, training of the operators is performed in the RTE facilities to improve their knowledge and to avoid any delays or misunderstandings during onsite maneuvers. Trainings on rare situations like black-start events is also important in order to prepare the operators if such an unlikely event occurs onsite. As an example, the Static Var Compensator HMI is shown in Fig. 10.

Fig. 9. Maintenance and training on replicas at RTE

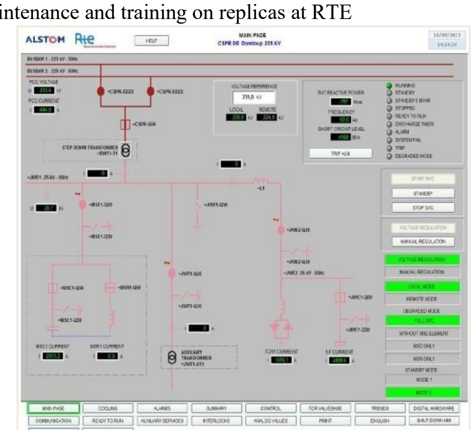

Fig. 10. Example of the Static Var Compensator HMI at RTE

VII. HIL Simulation for Training Cyber-Physical Energy Systems Professionals

A. *Educational needs and advantages of HIL simulation*

Apart from the traditional issues that power system operators must tackle, the digital transformation of the power system (e.g., digital substations, internet of things, on-line tariffs, or smart charging for electric vehicles) requires further power system professionals training in information technology (IT) and operational technology (OT) aspects with nearly all processes in a power system company being affected. For example, artificial intelligence is introduced to support planning, asset management, and operations, PMUs and power quality meters deliver high-resolution data of the grid status, and dispatchable and flexible assets are pooled on digital platforms to provide services. Besides the obvious IT/OT skills, cyber-security is often a new aspect that requires special attention in training.

B. *Reference teaching scenarios*

The "Controlroom of the Future" (CRoF) at TU Delft, Netherlands, offers power system professionals a training facility where they can be exposed to any cyber-physical crisis. The CRoF consists of the following items:

- Frontend: The control room itself, shown in Fig. 11, with video-walls, operator stations etc. This serves as an application-agnostic human-machine interface and does not host any other functionality.
- Backend: The university data center and high-performance computing center, and the DRTS-based power system digital twin cluster. This is where the system models (both electricity and communication systems), the SCADA software, the AI-modules, etc are hosted.

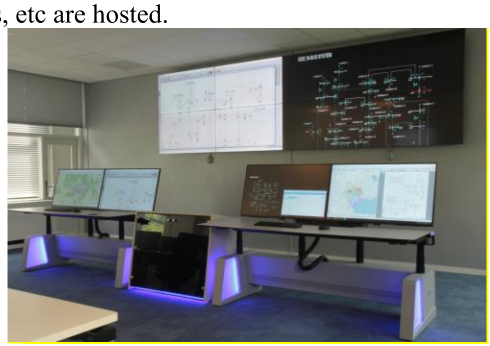

Fig. 11. The front-end of TU Delft's "Controlroom of the Future" for industrial training

These two parts are implemented and connected via a flexible virtualization environment that allows to easily switch from DSO "A" setup to DSO "B" or TSO "C" with all their grid models, IT/OT setups, SCADA software, etc. Another outstanding feature of this virtualization platform is that it offers full and customizable isolation between the individual parts. This is needed because the CRoF is also used for team red / team blue setups: training on cyber-security. Team red is the attacking team, while team blue is the defending team (typically the operators, IT and OT staff, plus management). The attackers might even use dangerous malware in order to prepare and execute their attacks. Containing such malware in a secure "cyber-range" is important. The setup, in the end, acts as a "cyber-physical range", since any switching action on SCADA, any change in (the simulated) weather, or any (simulated) equipment failure has an impact on the grid (simulation). The DRTS cluster with its grid twin and the control room are fully integrated. Some parts of the setup include actual hardware, since the DRTS offers HIL capabilities for testing PMUs, controllers, protection relays, and even power-hardware. The team red / team blue sessions proved to be very educative. It turned out often that communication between departments failed, or that certain situations were not anticipated. This insight can be the starting point of serious changes to prepare the company for cyber-resilience.

VIII. Remote Real-Time Simulation & HIL for Education Purposes

A. *Educational needs and advantages of HIL simulation*

Due to COVID-19 pandemic and to overcome an unprecedented need for a long time of social distancing, most universities worldwide adapted the traditional teaching methods, moving towards online learning. However, one of the most critical challenges in this transition has been laboratory-based practical classes. Practical classes are fundamental in the process of educating students, especially in engineering education. This section presents alternatives found by different universities to empower students to access remotely laboratories for practical activities. Using remote laboratories, the students can perform their empirical studies entirely in an online environment or execute part of the experiments before completing possible onsite investigations. The experience shows a new direction for educational development by combining the advantages of a real experiment with the remote access laboratory. Such approaches can complement the educational process, even during normal times.

B. *Reference teaching scenarios*

This section presents the practical activities used at Hochschule Bonn-Rhein-Sieg (H-BRS) in the "PHIL course" implemented remotely during the lockdown in Germany. This course is a cross-curricular course starting in the 3rd semester, which is linked with master and bachelor courses in Electrical Engineering, Mechanical Engineering, and Sustainable Engineering. The remote laboratory training applied during the lockdown provided the students with practical skills regarding the essential tools and methods for testing power systems and real-time simulation in PE. Each class included 15 students divided into teams of 5 students, with a duration of 1 hour. The primary teaching method consisted of using both lectures and practical activities to teach the fundamentals, the characteristics, the modeling, and the applications. The remote test bench was designed to introduce the student to the tools and methods of real-time simulation, HIL tests, and the practical aspects of power inverters. Two basic examples of practical activities developed by students were: i) investigation of PV power plants' integration in the electrical grid and ii) the functionalities and potential of large battery storage in the electrical grid. The simplified block diagram of the remote PHIL test rig setup is shown in Fig. 12. Fig. 12(a) shows the student's computer at home, while Fig. 12(b) shows the setup at the university: (b.1) shows the host-PC, and (b.2) shows the DRTS, where the power system is simulated. The hardware equipment is displayed in (b.3) and (b.4): (b.3) shows part of the hardware PV generation system, while (b.4) shows the microcontroller.

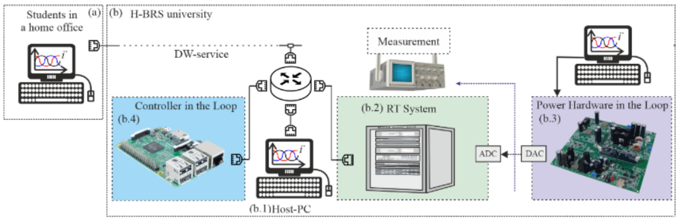

Fig. 12. Example of a remote PHIL experiment running in the laboratory

C. *Student feedback*

The overall feedback was very positive, with students appreciating the experiences of practical knowledge obtained remotely. During the lockdown, the instructor discussed the theoretical contents synchronously over video conferences. A strategy adopted to retain students engaged in the remote practical activities was the final exam based on group dynamics with presentation and discussion of the developed experiments.

IX. Model-in-The-Loop Simulation & Virtual Laboratories for Education Purposes

A. *Educational needs and advantages of Model-in-The-Loop simulation*

The concept of virtual labs is relatively recent, but definitely COVID-19 boosted it up, as universities were asked to move to online teaching in a very short amount of time. In this regard, a pilot project was launched in the fall of 2020 with five institutions from Canada, France, and Lebanon, which were given free licenses to use Model-in-The-Loop (MIL) virtual labs designed with (i) real-time simulation software and solvers under the hood, and (ii) an interactive GUI, packaged to run on students laptops in a standalone mode, thus not requiring any remote connection such as VPN or so. This pilot project got a great success in such a way that other institutions from Germany, UK, and Brazil joined the team starting from winter 2021. Additionally, today, it has been deployed in other countries around the world.

B. *Reference teaching scenarios*

The virtual laboratories cover a wide range of core electrical courses such as:

- **Fundamentals of electrical engineering**, where students learn about electric circuits laws, active AC and DC sources, passive loads mounted in various topologies, single- and three-phase transformers, harmonic analysis, balanced and unbalanced systems, etc.
- **PE converters** going through (i) choppers: buck, boost, and buck-boost, (ii) rectifiers: single- and three-phase, diode- and thyristor-based, (iii) inverters: two-level single- and three-phase, and (iv) three-phase three-level converter used both ways as inverter and rectifier.
- **Electrical machines** mastering the synchronous and asynchronous machines with the following concepts: parameters identification, generator and motor mode, connection to grid or to passive loads, variable-speed control, and short-circuit and recovery tests.
- **Electric motors drives** for (i) DC motor with linear torque and speed control, (ii) permanent-magnet synchronous motor with hysteresis-based self-control and vector control, (iii) squirrel-cage induction motor, and (iv) wound rotor induction motor both with vector control
- **Renewable energy sources**, where the following three elements are thoroughly explained: batteries, photovoltaic cells, and wind turbines. Then they are all put into a microgrid that can operate in islanded or grid-connected mode, feeding three types of loads, i.e., critical, partially flexible and fully flexible.

C. *Challenges and solutions*

The design of virtual laboratories faced many challenges, which were addressed as follows:

- Reproducing with high fidelity the real physical testbench. For instance, the electric machines virtual lab is the digital twin of the testbenches of the physical lab of electric machines located at Laval University, QC, Canada.
- Versatility: the student or the technician using the virtual lab should be allowed to employ various laboratory components when doing experiments and should not be constrained to rigid topologies or connections.
- Interactivity: the user should be in-the-loop, interacting with a GUI that allows them to connect/disconnect elements, observe and measure phenomena in real-time, etc.
- Being realistic: fuses are implemented on the virtual labs to protect various elements and show the users that although it is a virtual lab, still they must act in the appropriate way.

X. Recommendations for Effective and Safe Usage of DRTS and HIL Setups

Since this paper is dealing with real-time simulation and its advancements towards education and training on power and energy systems, an important part that should be discussed is safety concerns that may arise in some setups, especially PHIL setups. Some safety remarks applicable for PHIL simulation are presented, in a sequence of implementation. The aim is to provide an effective approach for the implementation of PHIL setups and for the provision of safety for students/instructors and machinery by avoiding failures or injuries. It should be noted that further research in this area would be useful.

In a fist step, the entire test case consisting of the PHIL simulation system serving as a reference document should be developed. In a following step, the careful selection and the modelling of the electrical equipment and key components integrated into the real-world and PHIL system should be performed. Then, stability and accuracy of the PHIL system should be analysed e.g. through the determination of the open-loop transfer function using the Nyquist stability criterion or the calculation of the system transfer function of the closed-loop PHIL system. Next, the real-world system and the corresponding experimental PHIL setup should be implemented in a suitable laboratory environment. A subsequent step involves the verification and validation process of safety measures and related systems. Requirements for laboratory-specific safety procedures and emergency shut-off circuits must be fulfilled at this point. Finally, the real-time based HIL simulation system should be initialised and executed with integrated safety measures on hardware and software level activated. Using such a procedure, investigations on electrical phenomena and functionalities under steady-state or transient conditions can be analysed in a safe, stable, and accurate way. More details on a methodology of preparing PHIL experiments in particular to avoid damages are given in [31].

XI. Conclusion

An analysis of the benefits that real-time and HIL simulation bring to distinct applications, such as power system dynamics, microgrids, PE, DER integration and transportation electrification is presented in this paper. Selected reference experiences of the Task Force members are presented along with data that substantiate the effectiveness of the presented approaches through the learners' feedback. Particular attention is given to training at the industry level, which has not been thoroughly addressed in literature so far, with special focus on both training of TSO professionals, but also to professionals in the emerging topic of cyber-physical systems. Remote and virtual laboratories are discussed, which have become increasingly relevant since the COVID-19 pandemic. Overall, based on the teaching scenarios presented and the positive feedback obtained, the value of real-time and HIL simulation for education/training has been clearly demonstrated, aiming to motivate the further usage of HIL for educational/training purposes in academia and industry around the world.

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