Co-Simulation Training Platform for Smart Grids

Thomas Strasser, *Senior Member, IEEE*, Matthias Stifter, *Member, IEEE*, Filip Andrén, *Member, IEEE*, and
Peter Palensky, *Senior Member, IEEE*

***Abstract*—Power systems training and education faces serious challenges due to the rising complexity of energy systems. This paper presents a simulation-based training platform for educating students and power systems professionals in complex Smart Grid applications. The system is split into parts like electrical grid or controls and specialized, domain-specific tools are then coupled to be able to simulate the overall behavior. Experiences with the developed education and training material and the corresponding modeling and simulation environment are discussed. The usage of advanced modeling and simulation approaches, especially when providing new functionality via coupling of simulation, is an accessible way to train and educate students efficiently in the complex and interdisciplinary area of power systems.**

***Index Terms*—Automation, power engineering education, power system analysis computing, power system control, power systems simulation, SCADA systems, smart grids, training.**

I. INTRODUCTION AND MOTIVATION

DRIVERS for the transition to an intelligent electric energy system are clearly the rise in renewable energy sources (RES) (e.g., wind, solar), electric vehicles (EV), more resilient network infrastructure, new market models and the goal of an emission free and sustainable energy system [1]–[3]. The need to understand the interconnections between the power system components increases steadily due to the rising complexity caused by the myriad of players and actors [4]. This includes not only the physical system but also the communication and the control of connected power components and assets [5]. These needs are addressed by recent developments and research in cyber-physical systems. As a result of this trend the focus needs to be put on educational aspects covering the transition in power systems towards a Smart Grid [4], [6], [7]. The aims of such a grid—as defined by the U.S. Department of Energy (DOE)—are the improvement of efficiency, reliability, economics, and sustainability of the electrical network by intelligent operation and control of suppliers and consumers [8].

Training and education can be based on the concepts of modeling and simulating components to understand how they work as a system [9], [10]. When designing intelligent automation and control concepts like energy management systems, voltage control algorithms, dynamic protection, topology re-configuration as well as demand response mechanisms, engineers need to understand different control paradigms, like centralized, hierarchical and distributed approaches. They also have to learn to use and know different tools and their strengths and weaknesses, and how to interconnect them [11]. Coupled simulation environments covering the previously mentioned areas are a promising approach to educate and train power systems students and professionals.

In classical simulation one tool respective its solver is used to integrate the model's equation. Multi-domain simulation tools separate the models and use more than one integrator, but are still a "closed modeling" approach. If two simulation tools or modelers are used to model subsystems separately which are re-unified into one equation system, than this is still a "closed simulation" but with "distributed models". When more than one simulation tool are used for modeling and for solving, then the "distributed simulation" of the "distributed models" have to be coupled; this is denoted as coupled-simulation or "co-simulation". Further details can be made on the modeling modularity (constraint vs. applied-force coupling) and on the interfaces (strong coupling via code-export or weak coupling via embedded function or variable exchange) [12].

In Smart Grids, skills and technologies are needed besides the traditional power engineering curricula [6], [13]. Topics related to automation (e.g., for the integration of renewables) as well as ICT (e.g., computer networks/protocols, cyber security) and including other physical domains are usually not covered by traditional training and education approaches.

The main contribution of this paper is the introduction of a co-simulation-based platform for training and teaching the systemic understanding of the ongoing changes in the electric energy systems today. This training environment addresses the continuing education of power system professionals as well as the education of power systems students, and covers the technical grid operation of active power distribution networks. Experiences from actual research projects, field tests and hands on laboratory demonstrations, supplement the implementation of a real world education exercise. Emphasis lies on the interconnection of different engineering domains—via interfaces to other tools—in order to learn how to cope with complexity by the co-simulation of components. A further focus lies on the introduction of the usage of free and open source software to motivate students to apply the programs outside of university courses for further research.

This article is organized as follows: Section II provides an overview of the related work. An analysis of the most important training and educational needs is given in Section III. In

---

Manuscript received June 07, 2013; revised October 11, 2013, December 17, 2013, and February 07, 2014; accepted February 07, 2014. This work was supported by the Austrian Climate and Energy Fund under the project *"DG-EV-HIL"* (FFG No. 827987). Paper no. TPWRS-00744-2013.

The authors are with the Energy Department, AIT Austrian Institute of Technology, 1210 Vienna, Austria (e-mail: thomas.strasser@ait.ac.at; matthias.stifter@ait.ac.at; filip.andren@ait.ac.at; peter.palensky@ait.ac.at).

Color versions of one or more of the figures in this paper are available online at http://ieeexplore.ieee.org.

Digital Object Identifier 10.1109/TPWRS.2014.2305740

Section IV the proposed co-simulation platform is introduced and discussed. The usage of this environment for educating master students and the training of laboratory personnel on future energy systems is presented in Sections V and VI. Lessons learned and experiences are discussed in Section VII followed by the conclusions ins Section VIII.

II. RELATED WORK

In the past, the individual technological areas—power system, components, communication and automation infrastructure—have been modeled and simulated in dedicated simulation packages. For example, steady state and transient stability simulation are very common for power systems analysis. A comprehensive overview of power system modeling and simulation methods with corresponding tools is provided for example by Milano [14].

For the simulation of ICT and automation aspects different simulation approaches and corresponding simulators are normally used [15]. The development of Smart Grids and related requirements urge for a more integrated simulation of all targeted domains [15]. Therefore, the usage of simulation methods as development approach is a very important and challenging topic [9], [10]. In order to simulate active power distribution networks, hybrid models combining continuous time-based (physics-related) and discrete event-based (communication and controls-related) aspects are needed. Usually, such multi-domain simulators are a challenging subject and only a few tools exist up to now [15], [16]. Nowadays, real-time simulations are getting more popular as development tools, since they allow a more realistic simulation setup as pure software-simulators [11], [17], [18]. Furthermore the simulation of communication and controls-related issues is covered by those real-time simulators and allow for (controller)-hardware-in-the-loop validation setups [19].

Summarizing, for the simulation of Smart Grid systems co-simulation environments are often preferred compared to pure multi-domain simulators (e.g., Matlab/Simulink, Modelica). As mentioned above, continuous time and discrete event models have to be combined in such a virtual system. Current research topics include the modeling of the different domain models in sufficient detail as well as the coupling of the different simulators [15]. The development of proper training, education material and courses is often not in the focus of these researchers but has to be covered in order to support the development of Smart Grid systems.

III. TRAINING AND EDUCATIONAL NEEDS

The understanding of the power distribution networks on medium voltage (MV) and low voltage (LV) levels due to the installation of distributed generators (DG), intelligent electronic devices (IED), power electronic components, smart meters, advanced communication networks and control strategies is challenging due to the rising complexity. In order to guarantee their functionality, availability, reliability and inter-dependability [20], an interdisciplinary understanding is necessary. These topics have to be addressed in proper training courses for power system professionals and students. In general, the following needs and requirements addressing educational aspects and related applications have to be dealt with [7], [13], [21], [22]:

- *Understanding electrical power system and components:* Covers the traditional topics (e.g., power systems and generation, electric machines, power electronics) of power system education [13], [23]. Special attention should be put on RES-technologies and their integration into the power systems.
- *Understanding communication networks:* Different network topologies as well as corresponding communication protocols for energy systems and power system automation (e.g., DNP3, IEC 61850) have to be targeted [4]. Center of interest should be the inter-dependency of the power system on smart sensors, control devices, control centers, protection equipment and end-users [23].
- *Understanding automation and control systems:* Introduction to advanced control possibilities in power systems, e.g., voltage control and power quality management is important. Further the basic principles of station automation (SA) and power systems automation (PSA) covering the concept of IEDs/RTUs (remote terminal unit) and protection equipment should be addressed by education [24], [25]. The concept and usage of supervisory control and data acquisition (SCADA) systems have to be introduced and explained as well.
- *Understanding Smart Grid principles and related applications:* The architecture of a power system with a high penetration of distributed energy resources (DER), electric vehicles and plug-in hybrids causing a bi-directional power flow, have to be addressed. Special emphasis should be put on applications and related functions like distribution automation/distribution management systems (DMS), demand response (DR)/demand side management (DSM), virtual power plants, microgrids as well as automatic metering infrastructures [1].
- *Overview and understanding of important standards:* According to international standardization roadmaps—proposed for example by IEC or NIST—the following core standards have to be addressed for the realization of Smart Grid systems with focus on interoperability between the different players: 1) SIA—Seamless Integration Reference Architecture (IEC 62357); 2) CIM—Common Information Model (IEC 61970/61968); 3) Power Systems Automation (IEC 61850); 4) Security (IEC 62351); and 5) Safety (IEC 61508) [26], [27].
- *Understanding systems by splitting it into parts:* The motivation for simulating a complex system by a co-simulation approach is that the respective part of the system under investigation can be modeled in the appropriate expert simulation packages. Modular and composite architectures enable compatibility and interoperability between tools and implementations. Especially where a real laboratory setup is missing or too costly (e.g., communication infrastructure, charging stations), a virtual environment is a helpful alternative. [12], [16]

These needs are currently not or only partly addressed by training software, tools and educational courses. Future requirements, recent developments and latest research results have to

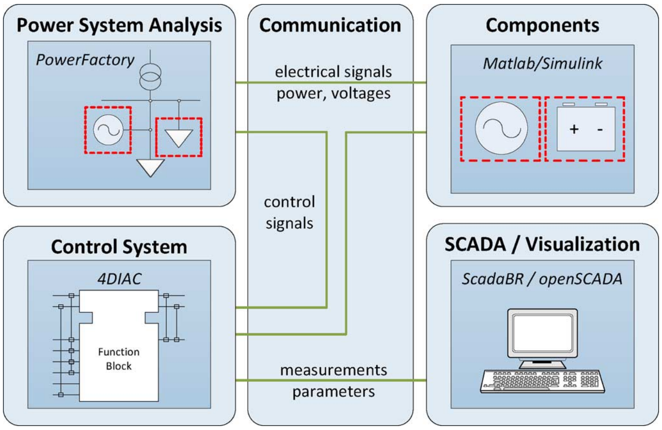


Fig. 1. Co-simulation-based training and education platform covering electrical system, power component, communication and automation topics.

be incorporated as well into the corresponding educational material addressing the future energy system. Therefore a simulation-based training platform covering the above described needs with emphasis on technical issues of active power distribution grids is introduced in the following section.

IV. Architecture of the Training Platform

In order to meet the above introduced training and educational requirements a co-simulation platform supporting the education of Smart Grid systems and corresponding applications is presented. This simulation-based platform comprises five important parts as shown in Fig. 1.

The general focus of this training environment is on the technical operation of MV/LV power distribution grids. Other aspects, like energy markets, economics and DMS, which are also very important domain topics are not covered, but could be integrated into the co-simulation environment as well.

Basic understanding of the model and simulation principles like continuous/time-discrete as well as time-continuous/event-based models is the foundation of the class. It is a goal to exemplify that classification into linear/nonlinear, time variant/invariant, continuous/discrete, concentrated/distributed parameters, deterministic/stochastic, is no absolute assignment, but will change according to the objective of the investigation and the real phenomena under consideration.

A. Modeling and Simulation of Power Distribution Networks

In order to simulate and analyze distribution grids, models of single and three phase networks, lines, loads, central and DGs are introduced, as well as conventional voltage control mechanism via on-load-tap-changers (OLTC) and reactive power. Dynamic simulation and interaction with controls and other continuous time or discrete event systems are explained.

1) Educational Aspects: The process of modeling electrical phenomena and components is a key skill in engineering and science. Different aspects of models and the behavior of dynamic systems are illustrated by examples from the power system domain like load models, electrical components and phenomena [23]. A particular important example is the difference between the balanced MV network and the unbalanced LV network, which requires accurate three phase/four wire modeling of the LV network. The statistical periodic (weekly, seasonal) and synthetic characteristics are not sufficient anymore for modeling loads in LV grids. Modeling the voltage transformer by step-wise considerations of real-world phenomena, like losses and stray flux, are elaborated. Actual research efforts and results regarding the use of OLTC MV/LV transformers are presented as an exercise to understand the requirements from within the system (problem identification: e.g., unbalanced system, voltage rise due to PV systems). The design and simulation of an intelligent control strategy for automatic voltage regulation is within the scope of the exercise. Alternative solutions like local voltage control by reactive power contributions of inverters, controlled charging and DSM are discussed and presented.

2) Tool Environment: Based on prerequisites of principle understanding of power system problems, the power system analysis tool PowerFactory is used for advanced modeling and analysis tasks. From single power flow solutions to the dynamic nature of the changing network situation is exemplified by the use of static load characteristics and by using the internal scripting language. This yield in investigation of time dynamic behavior and from steady state to stability analysis, using phasors. Additionally to the commercial and in the power system industry widely used simulation package, open source solutions are introduced and used in various examples: PSAT [14], [28] and GridLAB-D [29].

B. Modeling and Simulation of Grid Components

Even if many aspects of a power system simulation can be covered by a power system analysis tool it is sometimes necessary to model grid parts or components in much more detail. An example for this could be a detailed model of a PV system, a storage device or a control algorithm. This issue should also be supported by the platform to include simulations of such models, as depicted in Fig. 1.

1) Educational Aspects: An important part for understanding a complex system as a whole is to understand the functionality of single components and devices. This matter is addressed by the component simulation part in the training platform. With this tool grid components like DGs, controllable loads and storage systems can be modeled and analyzed in much more detail compared to the power system simulators where often simplified models are in use. One of the main challenges with the future power system is to cope with an ever increasing number of inverter-based grid components. Usually inverter systems introduce new possibilities (e.g., different ancillary services) but also challenges (e.g., introduction of harmonics). A deeper knowledge about these systems is important in order to understand the complexity of the energy system. Therefore the simulation of inverter-based grid components has priority in this part of the training.

2) Tool Environment: The analysis of inverter systems and power electronics can be done via specialized simulators like PLECS or GeckoCIRCUITS. However, to be able to cover multiple domains, Matlab/Simulink is used for the above introduced training platform. Simulink also offers many toolboxes specialized for the simulation of power systems and components, e.g., SimPowerSystems. An interesting benefit of using

Matlab/Simulink is the fact that other simulators and modeling tools can be connected using communication protocols or APIs. In addition, open source based tools like Octave, Scilab, or Rlab can be used for simulating grid components in general as well. Only GeckoCIRCUITS exists as open source approach for analyzing power electronic devices so far.

C. Automation System and Controller Design

Supervisory control, monitoring and diagnostics play important roles for the operation and optimization of transmission and distribution grids. Their interaction with distributed controllers and protection equipment (e.g., RTU, IED) have to be analyzed in detail. The training platform should also provide the possibility to implement control algorithms using domain-specific approaches. In this work the implementation of intelligent control algorithms for IEDs is explained based on the usage of the IEC 61499 reference model for distributed control systems [30] together with the interoperability standard IEC 61850 [31]. The integration of both standards is suggested in the literature as formal modeling approach for power utility automation devices [25], [32], [33]. Alternatively, the IEC 61131 programmable logic controller approach could be also applied [34]. An important aspect of this part is the teaching and education of the implementation and deployment of Smart Grid applications to the grid automation infrastructure.

1) Educational Aspects: The educational goal of this part of the training platform is the teaching of the basic principles of automation and control concepts and corresponding architectures. These lessons bring an overview to control, communication and SCADA/DMS systems as well as substation/power utility automation related topics. A special emphasis is on ICT standards for power utility automation in respect to communication, control and automation. Also the implementation of control algorithms using the above mentioned domain standards and approaches are covered.

2) Tool Environment: Besides the usage of commercial SCADA/DMS tools also free or open source-based implementations like ScadaBR, openSCADA, 4DIAC, etc. can be integrated into the co-simulation of automation solutions with power system topics. In the present implementation ScadaBR and 4DIAC are applied in the training environment.

D. Communication Network

Automation related communication not only enables a wide of possibilities and makes the energy system smarter, it also introduces additional dependability and reliability questions. The additional factor of requirement for communication needs to be evaluated and analyzed as well.

1) Educational Aspects: Creating awareness of communication and controllability aspects is the goal of this lecture. Issues regarding reliability—besides latency, bandwidth, and costs—are demonstrated by the use of a co-simulation environment setup and experiences from a real world demonstration project [35]. The need for different simulation mechanisms like offline-simulation, real-time simulation and even emulation need to be elaborated to explain the application fields for verification and controller/hardware-in-the-loop validations.

2) Tool Environment: For illustration purposes the data point oriented OPC server/client mechanism for process communication is demonstrated. The exchange of the data values introduce communication delays which has impact on the controller output [19]. As an example of communication infrastructure based voltage control, the co-simulation environment of the Austrian Smart Grid project "DG DemoNet Smart LV Grid" is used to demonstrate the realization of the simulation, validation and deployment process within one modular co-simulation environment. Moreover, popular commercial and open source based network simulators like ns2/ns3, OPNET, NetSim, OMNeT++, etc. can be included too.

E. Co-Simulation of Electrical Grid, Components, and Control

Beside the theory of coupled simulation (e.g., integrator or model-based coupling, interfaces), these lessons concentrate on interfacing different simulators. The focus is on the interconnection of the above introduced tools to form a co-simulation environment for investigating the system behavior of Smart Grids when applying various interacting distributed controls (e.g., voltage control, controlled charging of EVs).

1) Educational Aspects: Depending on the scope of the analysis, different coupling methods between the models (i.e., power grid, communication network, control algorithms and automation system) are being taught. This means that either a part of the co-simulation environment is used (e.g., power system analysis and automation topics) or the full setup. Also the possibility of a distributed simulation architecture on different computers is introduced.

2) Tool Environment: The physical models of the power grid and the components are continuous time based. The capability to dynamically interact with discrete time events is essential for coupled simulation of power systems together with dynamic controllers, inverter outputs, or sudden changes of loads (e.g., fuse tripping). The essential challenges are to synchronize the models, since they depend on each other. This can be done as introduced above by either combining the models into one big equation system and using one solver. The systems could iteratively exchanging their states at a certain moment in time until they converge or by introducing a simulation lag or error when the simulation uses the input from the previous time step. In real applications often a lag between the controller and the system under control is introduced because of time delays in communication or other effects like thresholds. The simulation step size of the individual simulators and the communication interval of the exchanged variables have to be chosen with respect to the simulation stability. Various interfaces for co-simulation exists in PowerFactory: Matlab/Simulink integration, access via OPC approach, integration with an external Dynamic-link Library (DLL), or even a dedicated Application Programmer Interface (API) [36]. A direct interface between Matlab/Simulink and 4DIAC is also possible using either OPC or through a simple TCP-based communication protocol [37].

In the following sections two selected educational and training examples are described using the above introduced co-simulation environment. The first one covers a master students' course related to the modeling and simulating of

TABLE I
OVERVIEW OF THE COURSE STRUCTURE

Course lectures	16
Lecture duration	4 hours
Student work (computer laboratory)	86 hours
European Credit Transfer System (ECTS)	6 points

complex power systems and the second one is dedicated to the training of personnel for a Smart Grid laboratory environment.

V. MASTER STUDENTS' CURRICULUM

A. Aim of the Curricula

The above described training platform has been successfully used in the first year of the four semester master program "Renewable Urban Energy Systems" at the University of Applied Sciences Technikum Vienna, Austria. This study program covers a broad range of related topics like "the expansion of renewable energies and their integration into urban power supply systems, intelligent networks for efficient power distribution, the reconciliation of power generation and consumption and holistic approaches to urban power distribution.

The goal of this course is to introduce the concept of Smart Grids and to educate the students to cope with the complexity of the interdisciplinary aspects of it (i.e., power system and ICT/automation infrastructure). A further goal is also to introduce modeling and simulation methods—especially co-simulation—for analyzing such a complex system. The development of control algorithms for operating and optimizing active distribution grids are covered too.

B. Structure of the Course

In order to show the different aspects of a complex energy system, the course is mainly divided into four parts. In detail, the modeling and simulation of the power systems, connected grid components (e.g., DGs, EVs, storages), control aspects and the co-simulation of them are incorporated. Especially, in the last part of the course the students are educated to combine the methods of the first parts using the training platform described above; the co-simulation principle is introduced as proper method for analyzing Smart Grids.

The duration of the whole simulation course is one semester (i.e., 2nd semester of the master's program). The same amount of lectures is used for teaching the electrical power system simulation, the grid component modeling, the automation/control system emulation and the co-simulation of Smart Grids. In addition, the students have to do some home work. They have to solve some modeling and simulation examples of the aforementioned topics. The analysis of communication issues is not covered by this curriculum due to time limitations. Table I provides a brief overview of the course structure.

C. Course Content

In the following the content of the different parts of this course is described in more detail.

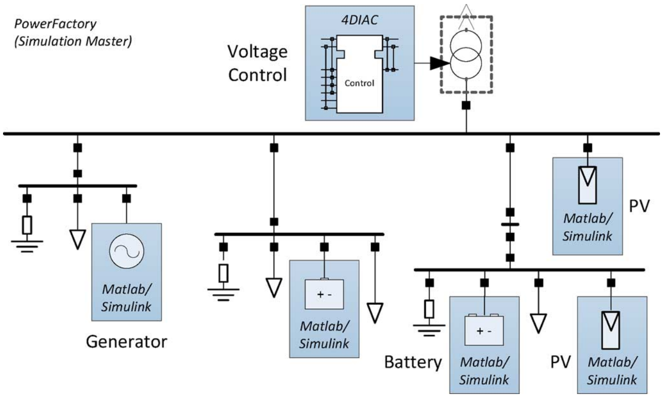


Fig. 2. Part of the LV grid modeled in PowerFactory. The internal controls and loads models can be replaced by coupling other simulation tools. The number of coupled simulators are not restricted to one.

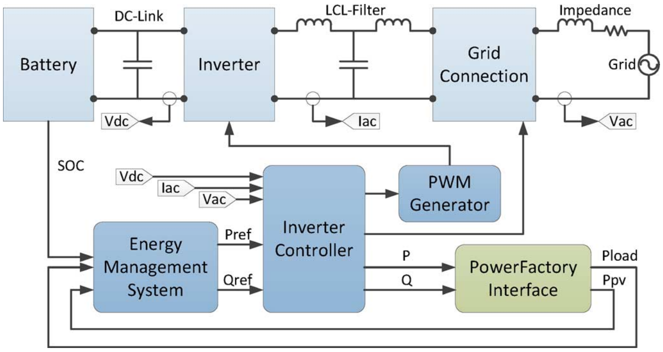


Fig. 3. Overview of the battery system and inverter models in Simulink.

1) Part I: Power System Modeling and Simulation: The first part of the course is intended to give the students a deeper knowledge about power system modeling and how to simulate different aspects of it. The goal of these lectures is to introduce the challenges of modeling and simulating LV networks with DGs, EVs, and local storages (e.g., battery systems) to the students. Only PowerFactory is used of the training platform to simulate the grid (see Fig. 2). Starting with a LV three phase/four wire network model, the task is to investigate impacts on the voltage symmetry and levels with different DERs (i.e., different generation profiles).

2) Part II: Grid Component Modeling and Simulation: This part of the course is dedicated to the modeling and simulation of inverter connected grid components. Throughout the related lectures a battery system interfaced with an inverter system to the power distribution grid is modeled. The simulation of the battery system is carried out with Matlab/Simulink. In Fig. 3 a sketch of the used model is shown.

The battery is modeled with a simple integrator using the battery output current as input. To model the inverter an H-bridge circuit is used with an LCL output filter. The interface to the electric grid is modeled as a voltage source in series with an impedance. A DQ-control scheme is implemented to control the inverter output current. The current controller takes two reference inputs, i_d^* and i_q^*, produced by a PQ-controller.

3) Part III: Control System Emulation: In the third part of the course the students learn the basics about automation and control approaches as well as how such systems can be implemented in a real environment. The usage of the IEC 61499 distributed automation reference model allows the engineering of so-called executable models [38], which brings modeling, simulation and implementation in a closer relationship. The goal of this part is to give the students a look into the development of control algorithms, but also to introduce the comprehensive automation infrastructure required for power utility automation. This means, SCADA/DMS systems, their functions and their interactions with distributed controllers are in the focus of these lectures.

4) Part IV: Co-Simulation: The final part is intended to analyze the interaction between the different parts of the curriculum. To show this, the whole co-simulation environment is used, i.e., PowerFactory for grid analysis, Simulink for the battery simulation and 4DIAC for control emulation.

The main goals of this part is to show the students the principals of co-simulation and to show how such an environment can be used to solve different problems in the area of Smart Grids. This is achieved by providing the students with a prepared setup of the co-simulation environment. Due to the time constraints of the course, focus is put on explaining the different interfaces between the parts of the training platform, e.g., the interface between PowerFactory and Simulink.

The co-simulation approach is explained using problem-based learning. The students are divided into groups where each group have a problem to solve using the training platform. The basic setup is for all groups the same, consisting of the distribution grid simulated with PowerFactory (shown in Fig. 2) connected with the battery analysis running in Simulink from Fig. 3. The grid model is also connected with a tap change controller in 4DIAC. The overall objective is to achieve the safe operation of the power distribution grid.

The first groups are responsible for extending the energy management of the battery system they have already developed in Part II of the course. By implementing different operation strategies (e.g., peak-shaving, demand-coverage [39]) the goal is to study how this affects the operation of the power distribution grid. For the second groups the goal is to implement an OLTC algorithm for the controller in 4DIAC, and also to study how the behavior of this controller affects the power distribution grid. An example of an OLTC algorithm implemented as IEC 61499 function blocks is depicted in Fig. 4. Using measurements of the voltage from the grid at critical nodes (i.e., lowest and highest voltage levels) the controller has to decide if the tap changer should tap up or down to adjust the grid voltage.

VI. TRAINING OF LABORATORY PERSONNEL

A. Aim of the Training Course

Another example where the platform has been successfully used is in the inverter test laboratory at the AIT Austrian Institute of Technology, where tests for inverter certification are made. The this environment has been designed for multiple inverter tests and thus includes many different functions and features. Due to the fact that the tests are designed to find out the limits of the inverters under test, the laboratory must be flexible enough for the operator to have full control. As a consequence many of the actions in the laboratory are critical ones where personal damage could occur. To avoid this the test engineers have to be trained before they are allowed to operate on the real laboratory equipment. With the co-simulation platform the laboratory can be virtually operated.

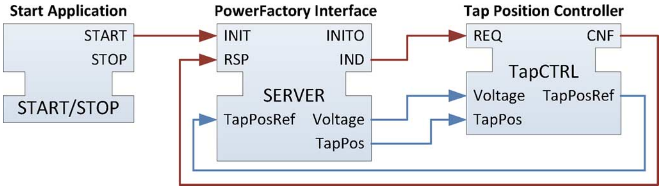


Fig. 4. Tap change controller algorithm developed in 4DIAC.

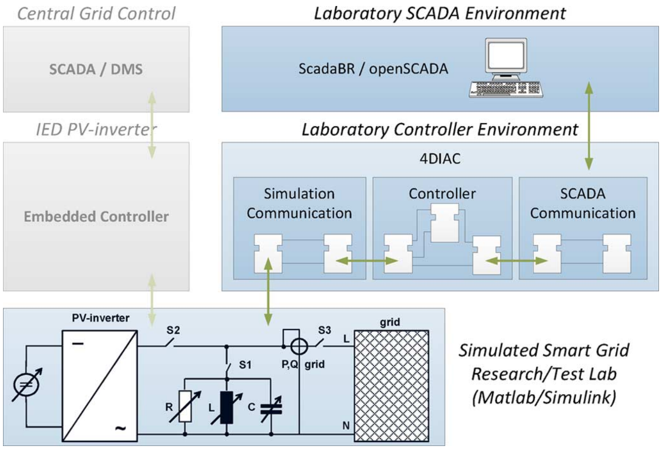


Fig. 5. Training scenario for test of PV-inverter anti-islanding functionality.

B. Training Example

To show how this kind of training is conducted, a test scenario according to the VDE V 0126-1-1 [40] rules is presented. This standard includes test procedures for validating the ability of PV-inverters to detect an electrical islanding condition and in such case automatically disconnect from the grid for safety reasons. One possible test method is to use frequency shifting of a tuned RLC-circuit. The test setup requires to adjust R, L and C elements installed in the laboratory grid to such values, that the real power P and the reactive power Q into the network equals zero $\pm 3\%$. Furthermore, the quality factor Q_f of the RLC-circuit needs to be $Q_f > 2$.

C. Usage of the Co-Simulation Environment

The setup for the training of this scenario is presented in Fig. 5. The laboratory SCADA system can be used as if it were connected to real test-stand. Thus, the operator (i.e., test engineer) can practice the different steps required for the RLC-circuit tuning for a successful test.

For this training course the component simulation, using Matlab/Simulink, the control emulation, using 4DIAC, and the SCADA component, using ScadaBR, have been used according to Fig. 1. The laboratory environment (i.e., grid, switches, RLC-circuit, PV array) as well as the PV-inverter (i.e., Hardware-under-Test—HuT) are modeled in Simulink, the controls for the laboratory are implemented in 4DIAC and the visualization is made using ScadaBR.

The training of the laboratory personnel is done in different steps. In the first step the engineer explore the different functions of the lab using the training platform on a normal PC. Both 4DIAC and ScadaBR can be used on a normal PC hardware and are connected via socket communication with the simulated laboratory hardware in Simulink. Measurements are sent from Simulink for the visualization in ScadaBR and any control actions performed by the test engineer(s) in ScadaBR, are sent to the simulation in Simulink. Alternatively the inverter controller as well as the utility DMS can be included into the training environment as depicted in Fig. 5.

To realistically simulate timing of the control actions the next step of the course uses a real-time simulation. As mentioned above, the whole virtual environment can be executed on a PC but also the real automation infrastructure (i.e., SCADA PC, controllers and corresponding software tools) can be used in a Hardware-in-the-Loop (HiL) setup. To have a more realistic timing behavior, the hardware model is implemented in a real-time digital simulator (i.e., Opal-RT). The interaction of the real-time simulation with the automation hardware is carried out using analogue and digital I/Os.

The final step of the course is to substitute the simulated laboratory environment with the real environment. Still 4DIAC is used for controlling the laboratory and ScadaBR is used for visualization. Following these steps a virtual laboratory environment is used for training the test engineers/operators. The test engineers can study and experiment with the different laboratory functions without having to worry about faulty operations. This approach minimizes the risk of damage for any critical actions in the real laboratory.

It has to be mentioned that this example has also been demonstrated to the students of the masters' course mentioned in the previous section during a visit of the AIT lab.

VII. DISCUSSION

A. Classroom Experience

The main aim of the master degrees' course was to teach students the ongoing changes related to Smart Grids. This means a combination of power system, control and ICT-related topics, realized with the presented co-simulation environment. Due to different educational backgrounds of the students, the course was divided into four main parts. The first three are on a basic level, covering power systems, components as well as control and automation. At the end of the third part all students had the same fundamentals on which Smart Grid topics can be covered. Since the same tools are used in the co-simulation environment as in the three introductory parts, the students could use the same models they developed in these parts of the course. From a teacher's point-of-view this highly facilitated the introduction of the co-simulation approach, and it was also one of the main positive aspects of the students' feedback. Moreover, another positive feedback from the students was to split each part of the course in a theoretic and a practical one.

Comments for improvement on the course was on decreasing the number of used tools. As a consequence more focus was put on PowerFactory and Simulink with which the students already had experience from previous courses. In the exercise part the students had to work in groups, where each group had to solve a problem with only two tools involved to keep the complexity low (e.g., voltage control with PowerFactory and 4DIAC, energy management with PowerFactory and Simulink). At the end each group presented their results to the whole class which is a good experience for the students. The presentations should on one side explain the solution achieved and demonstrate the advantage of this particular co-simulation approach on the other.

B. Overall Effort

The cost of such a co-simulation environment consisting of commercial tools is very low, because of the educational license model for PowerFactory and Simulink. The main consideration using these two simulators for the above presented course was that the students already had experience from previous courses, the provision of validated models and examples and the wide-spread use in industry. In general, if students are not familiar with this particular choice of simulation tools, the co-simulation framework can be realized with easy accessible, open source-based alternatives like PSAT, PST, OpenDSS, MatPower, or Octave [14], [41].

Another issue concerns the effort of coupling those tools. In the approach mainly one simple TCP/IP-based communication protocol offered by the 4DIAC environment has been used to couple the tools [41]. No adaptation was necessary in 4DIAC and ScadaBR, since both tools already support this protocol. The protocol was implemented in PowerFactory as well as in Simulink, and since both tools support custom interfaces, the effort was manageable. The communication principle and the corresponding implementation in PSAT/Octave as well as the coupling with 4DIAC is described in [41].

Summarizing, the overall effort in maintaining the above introduced training co-simulation environment is mainly related to the coupling of the simulators. This implementation only has to be updated if simulator interfaces change in new releases. Moreover, also the applicability with respect to reasonable costs of commercial tools have to be taken into account. Educational licenses are usually provided by tool vendors, but also various industry-recognized open source simulators exist as alternatives.

C. Outlook and Future Work

Custom developed interfaces between the simulation tools are lightweight, but often not very flexible and extendable for students. The coupling mechanism have to be realized and provided in advance and some interfaces are already available. Standardized simulation interfaces like the Functional Mockup Interface (FMI) enable the interaction of different domains and will help to investigate and understand difficult problems.

The future work will also be related to integrate communication issues in the developed education course. Also the topic of multi-agent based demand side management mechanism and market issues will be covered in a further version of the education co-simulation environment. It is also the goal of the authors to provide the developed solution as open source toolkit in the future for similar courses and colleagues from other university as a base for their own studies and teaching.

VIII. CONCLUSION

It is a common methodology to divide problems into smaller pieces. By applying this methodology to applications and challenges related to Smart Grids, it is possible to structure the problem into smaller subsystems and domains where existing analysis approaches and simulation models can be applied and analyzed. To investigate the interaction of the full system, the parts have to be connected again properly to validate the intended and investigate the not intended behavior.

This approach has been described and motivated in this article. An analysis of training needs and requirements shows that an approach from different engineering domains is necessary to achieve this goal. The co-simulation based training platform is presented in this work, covering traditional power systems topics, grid components, communication systems and automation infrastructure and therefore fulfilling the identified educational needs. In addition to the co-simulation approach the coupling of operation and control systems within real-time constraints bring together the domains of planning and operation. It enables the possibilities to validate simulation (e.g., power system) by connecting to production run-time systems (e.g., control system platform and SCADA).

The described training and education platform is used in a master degrees' course at the University of Applied Sciences Technikum Vienna. In addition, the training platform was also successfully used to train test engineers in a Smart Grid validation and test laboratory.

REFERENCES

[1] H. Farhangi, "The path of the smart grid," *IEEE Power Energy Mag.*, vol. 8, no. 1, pp. 18–28, 2010.

[2] Technology Roadmap Smart Grids. International Energy Agency (IEA), Tech. Rep., 2011 [Online]. Available: http://www.iea.org

[3] A. Vojdani, "Smart integration," *IEEE Power Energy Mag.*, vol. 6, no. 6, pp. 71–79, 2008.

[4] V. Gungor, D. Sahin, T. Kocak, S. Ergut, C. Buccella, C. Cecati, and G. Hancke, "Smart grid technologies: Communication technologies and standards," *IEEE Trans. Ind. Informat.*, vol. 7, no. 4, pp. 529–539, 2011.

[5] M. Liserre, T. Sauter, and J. Hung, "Future energy systems: Integrating renewable energy sources into the smart power grid through industrial electronics," *IEEE Ind. Electron. Mag.*, vol. 4, no. 1, pp. 18–37, 2010.

[6] V. Namboodiri, V. Aravinthan, S. Joseph, E. Sawan, and W. Jewell, "Five heads are better than one: An interdisciplinary graduate course on smart grids: Lessons, challenges, and opportunities," *IEEE Power Energy Mag.*, vol. 11, no. 1, pp. 44–50, 2013.

[7] A. Pahwa, W. B. Kuhn, R. Miller, and A. Rys, "Educational and research challenges and opportunities related to renewable energy," in *Proc. IEEE Power and Energy Society General Meeting*, 2011, pp. 1–3.

[8] The Smart Grid: An Introduction, U.S. Department of Energy (DOE), Tech. Rep., 2009 [Online]. Available: http://energy.gov

[9] M. Kezunovic, "Teaching the smart grid fundamentals using modeling, simulation, and hands-on laboratory experiments," in *Proc. IEEE Power and Energy Society General Meeting*, 2010, pp. 1–6.

[10] R. Podmore and M. Robinson, "The role of simulators for smart grid development," *IEEE Trans. Smart Grid*, vol. 1, no. 2, pp. 205–212, 2010.

[11] J. Martinez, V. Dinavahi, M. Nehrir, and X. Guillaud, "Tools for analysis and design of distributed resources—Part IV: Future trends," *IEEE Trans. Power Del.*, vol. 26, no. 3, pp. 1671–1680, 2011.

[12] M. Trčka, J. L. Hensen, and M. Wetter, "Co-simulation for performance prediction of integrated building and HVAC systems—An analysis of solution characteristics using a two-body system," *Simulat. Model. Practice Theory*, vol. 18, no. 7, pp. 957–970, 2010.

[13] J. Momoh, *Smart Grid: Fundamentals of Design and Analysis*. New York, NY, USA: Wiley-IEEE Press, 2012, vol. 63.

[14] F. Milano, "An open source power system analysis toolbox," *IEEE Trans. Power Syst.*, vol. 20, no. 3, pp. 1199–1206, 2005.

[15] H. Lin, S. Sambamoorthy, S. Shukla, J. Thorp, and L. Mili, "Power system and communication network co-simulation for smart grid applications," in *Proc. 2011 IEEE PES Innovative Smart Grid Technologies (ISGT)*, 2011, pp. 1–6.

[16] P. Palensky, E. Widl, and A. Elsheikh, "Simulating cyber-physical energy systems: Challenges, tools and methods," *IEEE Trans. Syst., Man, Cybern.: Syst.*, to be published.

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

[18] D. Anderson, C. Zhao, C. Hauser, V. Venkatasubramanian, D. Bakken, and A. Bose, "Real-time simulation for smart grid control and communications design," *IEEE Power Energy Mag.*, vol. 10, no. 1, pp. 49–57, 2012.

[19] F. Andrén, S. Henein, and M. Stifter, "Development and validation of a coordinated voltage controller using real-time simulation," in *Proc. 37th Annual Conf. IEEE Industrial Electronics Society (IECON)*, 2011, pp. 3713–3718.

[20] D. Kirschen and F. Bouffard, "Keeping the lights on and the information flowing," *IEEE Power Energy Mag.*, vol. 7, no. 1, pp. 50–60, 2009.

[21] A. Srivastava, C. Hauser, D. Bakken, and M. Kim, "Design and development of a new smart grid course at Washington State University," in *Proc. IEEE Power and Energy Society General Meeting*, 2012, pp. 1–2.

[22] S. Venkata, A. Pahwa, R. Brown, and R. Christie, "What future distribution engineers need to learn," *IEEE Trans. Power Syst.*, vol. 19, no. 1, pp. 17–23, 2004.

[23] F. Milano, *Power System Modelling and Scripting*. New York, NY, USA: Springer, 2010.

[24] S. Deshmukh, B. Natarajan, and A. Pahwa, "Voltage/VAR control in distribution networks via reactive power injection through distributed generators," *IEEE Trans. Smart Grid*, vol. 3, no. 3, pp. 1226–1234, 2012.

[25] N. Higgins, V. Vyatkin, N.-K. Nair, and K. Schwarz, "Distributed power system automation with IEC 61850, IEC 61499, and intelligent control," *IEEE Trans. Syst., Man, Cybern. C: Applicat. Rev.*, vol. 41, no. 1, pp. 81–92, 2011.

[26] SMB Smart Grid Strategic Group (SG3), "IEC Smart Grid standardization roadmap," International Electrotechnical Commission (IEC), Geneva, Switzerland, Tech. Rep. Ed. 1.0, 2010 [Online]. Available: http://www.iec.ch

[27] "NIST framework and roadmap for Smart Grid interoperability standards," National Institute of Standards and Technology (NIST), U.S. Department of Commerce, USA, Tech. Rep. NIST Publication 1108, 2010 [Online]. Available: http://www.nist.gov

[28] F. Milano, L. Vanfretti, and J. Morataya, "An open source power system virtual laboratory: The PSAT case and experience," *IEEE Trans. Educ.*, vol. 51, no. 1, pp. 17–23, 2008.

[29] D. Chassin, K. Schneider, and C. Gerkensmeyer, "GridLAB-D: An open-source power systems modeling and simulation environment," in *Proc. IEEE/PES Trans. and Distrib. Conf. Expo.*, 2008, pp. 1–5.

[30] *Function Blocks*, IEC 61499, International Electrotechnical Commission (IEC) Std., 2012 [Online]. Available: http://www.iec.ch

[31] *Communication Networks and Systems for Power Utility Automation*, IEC 61850, International Electrotechnical Commission Std., 2010 [Online]. Available: http://www.iec.ch

[32] German Commission for Electrical, Electronic & Information Technologies of DIN and VDE, The German Standardisation Roadmap E-Energy/Smart Grid Frankfurt, Germany, Tech. Rep., 2013 [Online]. Available: http://www.vde.com

[33] L. Zhu, D. Shi, and X. Duan, "Standard function blocks for flexible IED in IEC 61850-based substation automation," *IEEE Trans. Power Del.*, vol. 26, no. 2, pp. 1101–1110, 2011.

[34] *Programmable Controllers—Part 3: Programming Languages*, IEC 61131-3, International Electrotechnical Commission Std., 2012 [Online]. Available: http://www.iec.ch

[35] M. Stifter, R. Schwalbe, W. Tremmel, S. Henein, H. Brunner, B. Bletterie, A. Abart, F. Herb, and R. Pointner, "DG DemoNet: Experiences from volt/var control field trials and control algorithm advancements," in *Proc. 3rd IEEE PES International Conf. Exhib. Innovative Smart Grid Technologies (ISGT Europe)*, 2012, pp. 1–7.

[36] M. Stifter, R. Schwalbe, F. Andrén, and T. Strasser, "Steady-state cosimulation with PowerFactory," in *Proc. Modeling and Simulation of Cyber-Physical Energy Systems*, Berkeley, CA, USA, 2013.

[37] C. Landsteiner, F. Andrén, and T. Strasser, "Evaluation and test environment for automation concepts in smart grids applications," in *Proc. IEEE 1st Int. Workshop Smart Grid Modeling and Simulation (SGMS)*, 2011, pp. 67–72.

[38] V. Vyatkin, "IEC 61499 as enabler of distributed and intelligent automation: State-of-the-art review," *IEEE Trans. Ind. Informat.*, vol. 7, no. 4, pp. 768–781, 2011.

[39] F. Andrén, M. Stifter, T. Strasser, and D. Burnier de Castro, "Framework for co-ordinated simulation of power networks and components in smart grids using common communication protocols," in *Proc. 37th Annual Conf. IEEE Industrial Electronics Society (IECON)*, 2011, pp. 2700–2705.

[40] *VDE V 0126-1-1, Automatic Disconnection Device Between a Generator and the Public Low-Voltage Grid*, German Institute for Standardization (DIN) Std. VDE V 126-1-1, 2012 [Online]. Available: http://www.vde.com

[41] T. Strasser, M. Stifter, F. Andren, D. Burnier de Castro, and W. Hribernik, "Applying open standards and open source software for smart grid applications: Simulation of distributed intelligent control of power systems," in *Proc. 2011 IEEE Power and Energy Society General Meeting*, Detroit, MI, USA, Jul. 24–29, 2011.

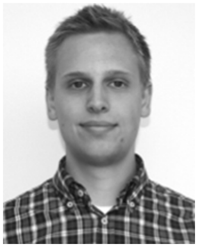
Thomas Strasser (M'09–SM'13) received the Ph.D. degree in mechanical engineering with focus on automation and control theory from Vienna University of Technology, Austria.

He is senior scientist at the AIT Austrian Institute of Technology in the domain of Smart Grids with focus on power utility automation. He was working for more than 6 years as a senior researcher at PROFACTOR research in the field of reconfigurable automation. He coordinated various projects in the domain of intelligent automation systems.

Dr. Strasser is a member of the IEC SC65B/WG15 maintaining the IEC 61499 standard. In addition, he is IEEE senior member of the IEEE societies IES, SMC, and PES and therefore involved in several technical committees.

Matthias Stifter (M'09) received a degree in technical cybernetics from Vienna University of Technology, Austria.

From 2003 to 2007 he worked at the Institute of "Computer Graphics and Algorithms" at Technical University of Vienna and at University of Technology Graz. Since 2007 he is with AIT Austrian Institute of Technology, Energy Department. His research interests include distributed generation, active distribution network planning, energy management and standards for communication and control in smart electricity networks. Since 2008 he is national expert for the IEA DSM Task XVII - Integration of DSM, DG, RES and Energy Storages.



Filip Andrén (M'12) studied applied physics and electrical engineering at Linkoeping University from 2004 to 2009 with a thematic focus on control and information systems where he received a master's degree.

Since 2009 he has been working as a scientist at the AIT Austrian Institute of Technology, Energy Department. He is specialized on smart grid and is working with power hardware in the loop as well as control and communication standards.

Peter Palensky (M'03–SM'05) is Principal Scientist at the AIT Austrian Institute of Technology, Energy Department. Before that, he was head of the Business Unit for Sustainable Building Technologies at AIT, CTO of Envidatec Corp., Hamburg, Germany, Assoc. Prof. at the University of Pretoria, South Africa, Department of Electrical, Electronic and Computer Engineering, University Assistant at the Vienna University of Technology, Austria, and researcher at the Lawrence Berkeley National Laboratory, California. His main research fields are complex energy systems and smart buildings.

Prof. Palensky is an AdCom member of the IEEE Industrial Electronics Society. He is active in international committees like ISO, IEEE, and CEN.