Hands-On Laboratory Course for Future Power System Experts

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***Abstract*—This paper describes the development of a modern power system laboratory within a Bologna Declaration compliant curriculum at the Department of Energy and Power Systems, Faculty of Electrical Engineering and Computing, University of Zagreb. The paper describes laboratory components and provides insight into the experiments that students are required to perform. The laboratory course is divided into three major components: power system simulations, computer simulations and high voltage. Power system simulations are performed on a miniature real-world power system that can be synchronized to the actual power system. Computer simulations are performed both on commercially available software solutions commonly used by power utilities and consulting companies, and on software tools developed at the Department of Energy and Power Systems. High voltage exercises are performed in the High Voltage Laboratory, where students are familiarized with high voltage phenomena. Results of student questionnaires collected over the previous four years are analyzed. This feedback, together with industry experts' observations and suggestions, provides the basis for improvements that are constantly introduced.**

***Index Terms*—Computer simulation, high voltage, power systems laboratory, student feedback.**

I. Introduction

THE Bologna Declaration [1] was signed by 29 European countries in 1999, adopting the new three-step university education system: bachelor, master, and doctoral studies. Today, the Bologna Process is implemented in national qualification frameworks of 47 European countries, including Croatia. The goal of the Bologna Process is to adopt unique degrees in order to facilitate mobility of students, graduates and higher education staff, as well as to prepare students for their future careers and lifelong education. At the Faculty of Electrical Engineering and Computing (FER), University of Zagreb, this involves a 3-year bachelor program, followed by a 2-year master program and a 3-year doctoral program.

The master program at FER covers three fields: Electrical Engineering and Information Technologies, Information and Communication Technologies, and Computer Science. Each field is divided to profiles, and Power Systems is a profile within the Electrical Engineering and Information Technologies field. Since the individualization of the classes that students attend is one of the main objectives of the Bologna reform, each profile consists of five mandatory courses, one laboratory course, and a minimum of 13 elective courses. Mandatory courses of the Power Systems profile are: Power System Analysis, Power System Dynamics and Control, Energy Transformations, Power System Economics, and High Voltage Techniques. Power Systems Laboratory is a compulsory course intended to ensure that all the students of the Power Systems profile acquire practical experience and skills, regardless of the elected courses.

Additional motivation for introducing this laboratory-only course is to increase the importance of laboratory exercises in master studies. When laboratory exercises were just a part of theoretical courses, the students were mostly focused on the theory-based exams since these accrued most points towards the overall grade. The low amount of points students could accumulate at laboratory exercises marginalized their significance. Introduction of the laboratory-only course rectified this shortcoming of the previous master program at FER.

Survey conducted in [2] recognized three shortcomings of today's engineering education: a need for more general engineering technical knowledge, a need for more hands-on experience, and higher level of professional awareness. The power systems laboratory at FER aims to contend these challenges by coupling theoretical knowledge acquired in lectures with laboratory experience required by the industry. Focused on problem-based learning, the laboratory course is intended to provide practical understanding of power system design, operation and control. The main goal is to enable students to apply and test theoretical knowledge they mastered in previous years of studies. The laboratory course enables them to develop practical skills in various fields of power engineering in a controlled environment. Furthermore, students are provided with the possibility of performing experiments and tests that would otherwise be either too expensive or nearly impossible to carry out in a real power system.

II. Literature Review

A multi-functional power systems laboratory at the Politecnico do Bari is described in [3]. This laboratory is used in bachelor, master, and doctoral studies. It consists of training

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systems (electrical measurements, programmable logical controllers, residential installations, and industrial installations), software simulation stations (power system modeling, simulation, and control), and the high voltage facility. This paper provides basic information about the laboratory, without describing the exercises.

An industry-sponsored power system laboratory at the Institute of Electrical Power Engineering, which serves fourth-year undergraduate students from the Province of Quebec, is described in [4]. The power system analysis course is mostly based on software tools, such as PowerWorld and Matlab. Exercises include power flow studying, fault analysis, and transient stability.

Power engineering laboratory at the University of Queensland is presented in [5]. In the final year of the bachelor program, students perform exercises focused on power system modeling, load flow analysis, fault analysis, transient and voltage stability, as well as the market structure. Exercises are performed using PowerWorld simulation software.

In [6], authors describe transmission and distribution systems analysis, operation, and planning laboratory. This laboratory is developed for the first year graduate students at the Drexel University. Authors thoroughly describe the hardware and laboratory setup, while the experiments are only briefly listed.

Power system protection undergraduate laboratory developed at Birla Vishvakarma Mahavidyalaya Engineering College, India, is presented in [7]. Experiments are focused on relay protection and are conducted in a substation-like operating environment.

A selection of power systems laboratory courses worldwide, including the one presented in this paper, is provided in Table I.

TABLE I
SELECTION OF POWER SYSTEMS LABORATORY COURSES WORLDWIDE

University	Washington State University
Course	EE 362 Power Systems Laboratory
URL	school.eecs.wsu.edu/undergraduate/ee/courses/362
University	UCLA
Course	EECS 163L Power Systems Laboratory
URL	plaza.eng.uci.edu/course/eecs/163l/outline/2011-2012
University	Ohio State University
Course	3047 Sustainable Energy and Energy Conversion Lab
URL	ece.osu.edu/course/3047
University	Drexel University
Course	ECE-P 461 High-Voltage Laboratory
URL	ece.osu.edu/course/3047
University	ETH Zurich
Course	Diagnostics, Measurement and Testing Technology in High Voltage Technology
URL	www.eeh.ee.ethz.ch/en/eeh/education/courses/viewcourse/227-0708-00s.html
University	RWTH Aachen
Course	Laboratory in Electrical Power Engineering I & II
URL	www.ifht.rwth-aachen.de/en/lehre/praktika/energietechnisches-praktikum-i-ii/
University	RWTH Aachen
Course	High Voltage Laboratory
URL	www.ifht.rwth-aachen.de/en/lehre/praktika/hochspannungstechnisches-praktikum/
University	TU Munich
Course	Laboratory Course on Energy Systems
URL	www.mspe.ei.tum.de/index.php?id=mw1869
University	TU Munich
Course	Laboratory Course on High Voltage Technology
URL	www.mspe.ei.tum.de/index.php?id=ei8010
University	TU Wien
Course	Energy Delivery Laboratory
URL	tiss.tuwien.ac.at/course/courseDetails.xhtml?windowId=b27&courseNr=373019&semester=2010W
University	University of Zagreb (FER)
Course	Power Systems Laboratory
URL	www.fer.unizg.hr/predmet/labele2_a

III. Laboratory Description

The laboratory course is divided into three major components:

1) power system simulations;
2) computer simulations;
3) high voltage.

The syllabus of the course is presented in Table II. This is a two-semester course that yields 5 ECTS points [8] per semester in the first year of the master studies. The course is performed in blocks of three academic hours per week, preceded by two academic hours of lectures addressing the current exercise. All exercises are performed within a single week, which results in 19 weeks of laboratory exercises. Since each semester spans over 15 weeks, the additional 11 weeks are allocated for exams (two weeks in each semester), visits to power system facilities (two weeks in the second semester), and for re-doing exercises for students who were unable to attend them according to the schedule (five weeks over both semesters). Students perform exercises in groups of twelve and then break down to smaller groups, depending on the type of exercise. Computer simulation exercises are performed individually, while power system simulation and high voltage exercises are performed in groups of two to three. Students are required to submit a report after each exercise. Reports account for 50% of the overall grade, while the remaining 50% is based on written examinations.

Each exercise is designed to introduce students to a specific aspect of power system related issues. Learning objectives, according to the Bloom's taxonomy [9], are provided after the description of each exercise in the following section.

IV. Laboratory Exercises

A. Exercise 1: Generator Stability

This exercise is performed on a miniature power system that consists of the following:

- Model of a thermal power plant (1 in Fig. 1) with primary equipment: motor simulating a thermal turbine, generator with busbars, circuit breaker and feeder disconnector; and secondary equipment: current and voltage transformers, protective relays, and power plant control system, including network synchroscope.
- Model of a run-of-river hydro power plant with a Pelton turbine (2 in Fig. 1) with nominal flow of 27 l/s. Underneath the turbine is a water reservoir with 7000 liter capacity. Water from the reservoir is pumped to the turbine, thus simulating the penstock.

TABLE II
SYLLABUS (CS-COMPUTER SIMULATION, PSS-POWER SYSTEM SIMULATION, HV-HIGH VOLTAGE)

	Exercise	Description	Type
Semester 1	1	Generator stability	PSS
	2	Fuses	PSS
	3	Grounding in power facilities	PSS
	4	Temperature rise analysis	CS-GOTHIC
	5	Cooling tower analysis	CS-GOTHIC
	6	Power flows	CS-PSS/E
	7	Short circuits	CS-NEPLAN
	8	Distribution network structures	CS-CADDiN
	9	Distributed energy sources	CS-CADDiN
	10	Introduction to graphical programming	CS-LabVIEW
	11	SCADA design	CS-LabVIEW
Semester 2	12	Stationary heat conduction	CS-ALGOR
	13	Introduction to the market simulator	CS-MaSi
	14	Spot market trading	CS-MaSi
	15	Combined spot market and bilateral contracts trading	CS-MaSi
	16	Generation and measurement of high voltage	HV
	17	Distribution of electric potential on insulator chains	HV
	18	DC voltage	HV
	19	Impulse voltage	HV

Fig. 1. Miniature power system (1—thermal turbine; 2—hydro turbine; 3 rigid network).

- The rigid network (3 in Fig. 1) is the utility grid, to which the two power plants can be synchronized.
- Transformer substation, fully equipped with circuit breakers, feeder disconnectors, current and voltage transformers, protection devices and control circuits.
- Different loads connected to the power system model.
- A series of line models with circuit breakers and feeder disconnectors simulating a high voltage power system network, similar to the concept described in [10]. Line parameters and network topology may be changed.

In the first experiment students are required to synchronize the generator to the power network. This tests their knowledge of requirements for successful synchronization, i.e., the generator needs to have the same voltage, frequency, order of phases and phase angle as the rigid network. Students also need to know what would be the consequences of not meeting these requirements.

In the second experiment the generator is connected to the power system by a single line. The goal is to capture generator dynamics (machine swing curve) after opening and quickly reclosing the line.

In the third experiment the generator is connected to the power system by two parallel lines. The goal is to measure the generator load angle after one line is switched off. For that purpose, a stroboscope, synchronized with the power system, is used. Since the generator is a six-pole machine, its shaft is marked with three white and three black areas. Every white area is divided into nine parts, each corresponding to electrical 20°. In the normal operation both lines are closed and a fixed needle points at the electrical load angle which students note. After opening one line, students note the difference in the load angle. The experiment is repeated several times for different line loadings.

Learning objectives: 1) demonstrate synchronization of a generator to the power network; 2) estimate and analyze generator load angle dynamics.

B. Exercise 2: Fuses

The aim of Exercise 2 is to familiarize students with metal wire fuses and automatic fuses that are used for overcurrent protection of electric circuits. Students are introduced to the basic phenomena that occurs in the fuses in case of an excessive current flow. The operating principles of wire fuses and automatic fuses are exposed.

Energy consumed by the fuse element to clear the electrical fault is discussed, along with other characteristics such as speed, breaking capacity and rated voltage. The characteristics and role of a bimetallic strip is explained.

After the theoretical part, students perform an experiment in which a fuse breaks the short circuit current. During this experiment, voltage and current characteristics of fuses are recorded. Students study energy characteristics of different fuses and the time it takes to extinguish an electric arc.

Learning objectives: define the application area of different fuse types.

C. Exercise 3: Grounding in Power Facilities

The aim of this exercise is to familiarize students with the means of measuring ground resistance. These measurements are essential for the safety of workers at power and industrial facilities. The exercise consists of four parts: specific ground resistance, electric potential distribution in the ground, step and touch voltage, and lightning rod testing.

Specific ground resistance is measured using the Wenner four-pin method. Setting pins to different distances, students measure ground resistance at different depths. They are required to draw a resistance versus depth diagram.

The goal of the second part of the exercise is to determine the distribution of electric potential, as well as the potential related to the referent neutral ground. Students use the low voltage $U - I$ method. A short circuit is simulated by injecting a current through the ground electrode being analyzed. Since this is a low voltage measurement, there is no danger for students or the facility. Students are required to note the potential along all

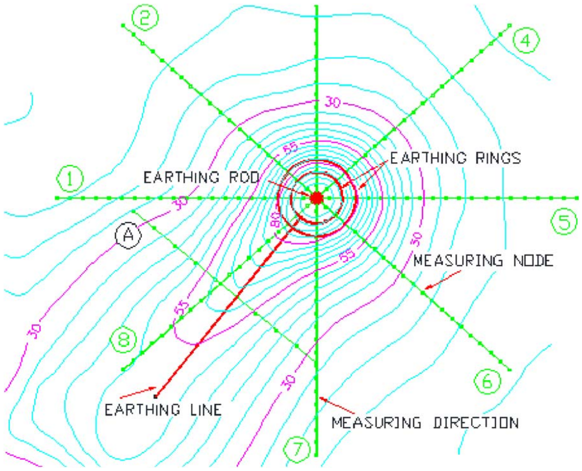

Fig. 2. Example of a student diagram showing equipotential curves.

directions and draw appropriate diagrams. An example of a student diagram showing equipotential curves is provided in Fig. 2.

In the third part of the exercise students are required to measure step voltage at various locations and touch voltage of metal objects around the Faculty grounds. In the end, they are supposed to assess the integrity of the grounding system.

In the final experiment students use voltage and current clamps to assess the state of the lightning rod system. Voltage clamps are used to induce voltage, while the current is measured using the current clamps. This method is convenient because no ground stakes are needed.

All experiments are carried out on the ground next to the Faculty building, using local lightning rods and additionally buried ground electrodes.

Learning objectives: 1) explain ground resistance measurement; 2) assess integrity of a grounding system.

V. Computer Simulations

A significant number of power systems students at FER will find their future employment with the National Power Company, Koncar (leading producer of power equipment in Croatia), energy institutes or consultant companies. For this reason, the power network simulation exercises aim to provide them with a wide knowledge of the power system simulation tools they will be using in the future. These exercises are designed to emulate specific issues of the Croatian power system, both the transmission and distribution grid. The simulation tools used are PSS/E [11] and NEPLAN [12], well known tools applied in different areas of power system planning and analysis. These exercises are based on real case grids from industry projects with the National Power Company and other investors, e.g., [13] and [14].

A. Exercises 4 and 5: Temperature Rise and Cooling Tower Analysis

In these exercises students perform analysis of heating parameters of critical equipment at a nuclear power plant. For this purpose they use GOTHIC (Generation of Thermal-Hydraulic Information for Containments) simulation package [15].

In Exercise 4 students are required to analyze the temperature increase in rooms with electrical equipment and calculate the temperature of a 6.3-kV power cable. This room contains a pump and pipes supplied by an electric motor. A water-air type heat, ventilation and air-conditioning (HVAC) device starts simultaneously with the pump. The required room data are temperature, humidity, pressure, room dimensions and insulation parameters. Cable parameters are its dimensions, material and current. Students need to model both active (electric motor, ventilation motor, pump losses, lighting, pipeline and electric cable) and passive heat sources.

Exercise 5 is focused on modeling of a cooling tower with ventilated circulation. A cooling tower is divided into cells. Hot water is injected at the top of the cooling tower through a set of nozzles. The lower part of the tower contains a pool for cooled water. Evaporated water is replaced by fresh water at atmospheric temperature. For a set of parameters (ventilator volume flow, cell height and volume, nozzle diameter, water flow and temperature, initial volume of water in the pool, atmospheric conditions, cooling tower geometry), students need to perform a simulation for a 1000-s time frame. They are required to graphically show changes of temperature and air in the cooling tower, relative humidity and water evaporation. Also, students need to graph overall water evaporation and flow of fresh water, as well as cooling tower power and pool water level dependent on time.

Learning objectives: 1) identify heat sources and sinks and calculate ambient conditions influencing electrical equipment operation; 2) define and analyze dependence of operational parameters in cooling towers and similar heat transfer devices.

B. Exercise 6: Power Flows

Exercise 6 introduces transmission system operation to students. Problems assigned to students are based on the Croatian transmission system and point out several important issues that the Transmission System Operator (TSO) faces on a daily basis. Namely, a specific layout of the Croatian transmission grid results in distinct voltage and congestion problems. Seasonal and daily electricity consumption variations, as well as the role of the Croatian power system in electricity transport from Eastern to Western Europe, result in difficult load flow management. The most troublesome are the low consumption periods [16]. Hence, students learn on a realistic transmission system, similar to the one they will encounter during their employment.

In this exercise students analyze different seasonal and daily consumption profiles. Electricity transport scenarios and wind power plant output scenarios are considered as well.

Learning objectives: calculate and analyze steady state power flows in the network.

C. Exercise 7: Short Circuits

Exercise 7 is structured to familiarize students with short circuit issues in transmission and distribution networks. The exercise is performed on a real network with emphasis on several important issues:

- impact of electrical distance between generators on short circuit current values;
- impact of transformer vector group on a single phase short circuit values;

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- capacitive short circuit problems and grounding solutions.

Students perform a sequence of simulations varying transmission/distribution system layout (based on actual planning strategies), connecting new generating units and altering transformer vector groups.

Learning objectives: classify faults in electrical power networks and to calculate fault current values.

D. Exercises 8 and 9: Distribution Network Structures and Distributed Energy Sources

Exercises 8 and 9 provide a comprehensive overview of techniques used in distribution system planning and analysis. Students are first introduced to a distribution system planning tool CADDiN [17]. This tool has been developed at the Department of Energy and Power Systems at FER. It solves problems of optimizing a distribution system layout. Students are also introduced with planning principles, methods of identifying the optimal separation point, as well as optimization algorithms [18]. In Exercise 8, students perform the following calculations and analyses:

- sensitivity analysis for CADDiN input data;
- distribution grid layout optimization based on minimizing losses;
- distribution grid layout optimization based on minimizing voltage drops;
- checking and comparing the results of *manual calculations* to those performed by a specialized software, such as NEPLAN, on a simple distribution grid.

In Exercise 9, students deal with a distribution network that contains distributed generation (DG). Current policy in Croatia stimulates DG regardless of the point of connection. Performing simulations on a real Croatian distribution grid, students learn the following:

- Optimal placement of the DG with the goal of postponing grid reinforcement investments
- Changing its operating point, DG can produce reactive power on the account of active power and thus improve voltages in the grid
- DG with variable output, such as renewable energy sources (RES), can impact the distribution network voltage profiles, depending on the connection point
- Modeling voltage harmonics impact of DG to the distribution network power quality

Learning objectives: 1) explain the choice of a distribution network structure; 2) analyze impacts of a distributed energy source on the network.

E. Exercises 10 and 11: Introduction to Graphical Programming and SCADA Design

These exercises introduces students to graphical, general-purpose programming language, called G used in the LabVIEW [19]. Due to its extensive use in teaching and research, FER is the host of the LabVIEW Academy in Croatia.

The aim of Exercise 10 is to provide introduction to graphical programming and its application to solving real-world engineering problems. Graphical programming resembles a series of interconnected function blocks on a block diagram. Since block diagrams are something they use on a daily basis during their studies, students should quickly understand the concept.

The aim of Exercise 11 is to apply graphical programming to the design of SCADA (Supervisory Control And Data Acquisition) for power systems. During the lecture students are introduced to techniques required for applying graphical programming to design a simplified SCADA system. Laboratory exercise consists of developing a program and configuring hardware used for automation and control of a circuit breaker and a disconnector in the substation. Additionally, students need to display the measured values obtained by digital multimeter (current, voltage, frequency, etc.).

Once the students have successfully solved the problems in Exercise 11, they should have a basic knowledge of the design of HMI (Human Machine Interface) and communication with the equipment in the substation.

Learning objectives: design graphics-based systems for data collection and analysis.

F. Exercise 12: Stationary Heat Conduction

This exercise is designed to provide understanding of basic concepts of heat transfer: conduction, convection and radiation. Followed by theoretical and mathematical introduction to the exercise, students are given assignments to model and simulate stationary heat transfer using the ALGOR software [20]. Assignments include modeling of a transmission cable and calculating the increase of cable and environment temperatures due to conducting current. In this exercise students learn how to model a power cable composed of 2-D elements and simulate cable heating caused by current, as well as heat transferred in the surrounding environment (air or water).

Once they learn the basics of modeling, students perform several analyses for different cables and environments. A more complex exercise would be to develop 3-D models. However, experience has shown that this requires more laboratory time and such calculations are usually performed only by smaller groups of students in specialized courses.

Learning objectives: classify and model all three types of heat transfer.

G. Exercises 13, 14, and 15: Introduction to the Market Simulator, Spot Market Trading, and Combined Spot Market and Bilateral Contracts Trading

On top of the technical knowledge, a modern power engineer is expected to understand the operation of electricity markets [21]. In Exercises 13, 14, and 15 students use software MaSi [22], developed at Trondheim University, to simulate the operation of an electricity market. They are required to analyze various situations and draw relevant conclusions. Experiments begin with a demonstration, followed by individual student simulations. Students learn by facing different situations in the market and analyzing their outcomes.

In Exercise 13, students are familiarized with the software and its capabilities. Students can test their knowledge from the lecture that accompanies these exercises. They learn about both physical and financial products in electricity markets, the concept of market splitting as a congestion management tool, orga-

Fig. 3. High voltage laboratory.

nizing electricity markets in balance groups, and the role of the Market Operator (MO) and the TSO.

Exercise 14 contains two experiments. In the first one students consider problems when all market participants own diverse generation facilities, which limits their opportunities to exercise market power. In the second experiment market participants own distinct generation portfolios, i.e., one participant controls most of the hydro generators, while the other one controls most of the thermal generators. This type of market structure may result in exercising the market power, which students need to recognize and comprehend.

In the final exercise with MaSi software students combine spot market trading with bilateral contract trading. Students are required to identify advantages and disadvantages of spot market as compared to the bilateral trading.

All exercises are based on the Croatian power system with actual transmission constraints. This enables better student perception of the exercises and takes into account exercising of market power as a result of congestion and portfolio structure.

Learning objectives: 1) explain and analyze the trading process at the electricity market; 2) prepare trading bids regarding available assets.

VI. High Voltage Laboratory

The High Voltage Laboratory at FER, shown in Fig. 3, is accredited for *high voltage power frequency testing of electrical equipment and testing (measuring, calculation and estimation) of electromagnetic fields frequency 50 Hz according to the norm ISO/IEC 17025:2007* issued by the Croatian Accreditation Agency. Since the equipment is used to perform commercial testing, students are familiarized with industry testing procedures.

For safety precautions and value of the equipment, most experiments are preformed by a laboratory technician, while students write down the results and perform calculations.

A. Exercise 16: Generation and Measurement of High Voltage

This exercise consists of 5 demonstrative experiments.

The goal of the first experiment is to familiarize students with the corona issue and means of preventing it. A regulation transformer is used to raise the voltage of a conductor located in the center of a grounded metal cylinder. Various conductors are tested and voltages at which the corona occurs are noted.

Tests using AC voltage at industry facilities need to be conducted with a sinusoidal voltage that should not deviate from ideal sinusoidal waveform by more than 5%. In the second experiment, a stripped copper wire connected to an oscilloscope probe is placed on the insulated surface underneath the bus. After energizing the bus, as a result of capacitive coupling between the bus and the copper wire and between the copper wire and the ground, the oscilloscope will display the same waveform as the high voltage transformer. Students capture the voltage waveform in the entire range of the high voltage transformer.

In the third experiment a spherical spark gap is used for measuring high voltage. After setting a voltage on the low voltage side of the transformer, spheres are slowly brought closer together. After an arc appears, the distance between the spheres is noted. This procedure is repeated six times. The first reading is discarded because the air between the spheres has not been ionized yet. Based on the remaining five measurements, students calculate the average distance and read the breakdown voltage using a conversion table.

In the fourth experiment voltage is measured by using a capacitive voltage divider and electrostatic voltmeter. Based on the reading of electrostatic voltmeter and condensers capacity ratio, students calculate the measured voltage.

In the final experiment AC voltage is measured by measuring the current flowing through the known susceptance. Half wave or full wave rectification may be used.

Learning objectives: 1) describe the importance of high AC voltage testing; 2) design experiments for high voltage generation and measurement.

B. Exercise 17: Distribution of Electric Potential on Insulator Chains

Although electric potential is not uniformly distributed along the overhead line insulator chain, there is a certain regularity. Most voltage is on the lowest insulator, the closest one to the conductor. In the upward direction, the voltage on the insulators decreases until approximately two thirds of the insulator chain. After that, the voltage on the insulators increases again.

Assessing voltage integrity of the insulator chains is a two-step procedure. In the first step, a single insulator within the chain is touched with an insulated pole with a sphere at the tip. After moving the sphere away from the insulator, a spark will appear between the insulator and the sphere. The sound that can be heard is louder as the insulator voltage is higher. This procedure is used to assess the condition of insulators within the insulator chain.

In the next step, an insulated test fork is used to bridge individual insulators. Again, the louder the sound, the higher the insulator voltage.

In case an insulated fork with a spherical spark gap is used, the exact voltage of each insulator within the chain can be calculated. The experiment is performed in two runs, with and without the protective ring. In this way, students observe the impact a protective ring has on the distribution of voltage among the insulator chain.

Learning objectives: 1) interpret results of individual insulator voltage measurements and 2) assess the integrity of an insulator chain.

C. Exercise 18: DC Voltage

In this exercise students are familiarized with means of generation and measurement of high DC voltage.

In the first experiment high DC voltage is generated by rectifying high AC voltage using a mechanical rectifier and a high voltage diode limited to 100 kV. Rectified voltage is smoothed using six serial connected medium voltage condensers.

In the second experiment two ways of high DC voltage measurements are presented to students: using the spherical spark gap and instruments in a potentiometer connection. When using the spherical spark gap, the polarity issue arises, which students need to realize. They are also required to calculate the ratio of low AC voltage and high DC voltage.

In the third experiment theoretical formulae for breakthrough in homogenous and close to homogenous electric field are verified. For this purpose a cylindrical condenser is used. The condenser consists of a wired tube, which acts as a ground and two cylinders with different diameters that have an electric potential. A 50-mm diameter cylinder inside a wired tube with 70-mm inner diameter creates a homogenous electric field, while a 16-mm diameter cylinder inside the same wired tube creates a close to homogenous electric field. Before performing the experiment, students are required to calculate a breakthrough voltage for two combinations of electrodes, and compare those to actual values during the experiment.

Learning objectives: 1) design experiments for high DC voltage generation and measurement; 2) explain the difference between homogenous and close to homogenous electric field.

D. Exercise 19: Impulse Voltage

In this exercise students are familiarized with generation and measurement of impulse voltage, as well as performing tests using impulse voltage. Students also learn the operating principle of the surge arrester. All experiments are performed using both positive and negative polarity.

In the first experiment students learn how to generate a high impulse voltage by discharging high voltage and high capacity condenser into circuit. The condenser is charged using the high voltage diode, a procedure described in the previous exercise. An impulse voltage of 95 kV is generated.

The problem with measuring high impulse voltage is its short duration. A spherical spark gap is adjusted until it breaks 4–6 times within 10 measurements. For comparison, a DC voltage on the charging condenser at the moment before the break occurs is measured as well.

In the third experiment an impulse breakthrough voltage of a supporting insulator is measured. Again, a spherical spark gap with a 50% breakthrough method is used.

The last experiment is designed to demonstrate the protection function of a surge arrester in case of a high magnitude overvoltage. It is shown that the surge arrester actions are independent on the polarity. The surge arrester is connected in parallel to the protected device. A digital oscilloscope is used to display an overvoltage and leftover voltage at the surge arrester.

Learning objectives: 1) generate and measure impulse voltage; 2) explain the operation principle of a surge arrester.

TABLE III
RESULTS OF THE STUDENT QUESTIONNAIRE (GRADES: 1—STRONGLY DISAGREE; 2—DISAGREE; 3—NOT SURE; 4—AGREE; 5—STRONGLY AGREE)

Year	2009/10	2010/11	2011/12	2012/13
Students who took the poll/ Overall number of students	35/120	13/92	63/111	6/71
Course was well organized	3.68	3.36	4.36	4.14
Goals of the course were clear	3.64	3.27	4.39	4.67
Grading scheme was clear and fair	3.68	3.64	4.58	4.67
My prior knowledge was sufficient for the course	4.07	4.18	4.39	4.33
Teaching materials were helpful	3.56	3.20	4.30	4.00
Course tasks were of appropriate duration and complexity	3.68	3.36	4.36	4.14
Laboratory procedures were well prepared	4.00	3.50	4.38	4.59
Homework was adequate	3.83	4.00	4.26	4.33
Homework and tests grading provided a useful feedback	3.79	3.25	4.38	4.67
In average I spent: 1 (<2h); 2 (2-4h); 3 (4-6h); 4 (6-8h); 5(>8h) preparing for the course	2.31	1.73	3.29	4.00
Course was well paced	4.14	3.86	4.44	5.00
Lecturers instigated my interest in the course	4.37	3.78	4.41	5.00
Lecturers gave clear and easy to follow lectures	4.33	3.96	4.55	5.00
Lecturers encouraged students to discuss and interact	4.28	3.53	4.40	4.67

VII. EVALUATION AND IMPROVEMENTS

A. Student Feedback

At the end of the academic year students voluntarily and anonymously answer a questionnaire. Questions and average scores in the previous four years are shown in Table III.

Students' answers suggest that the organization and clarity of the course, as well as teaching materials and laboratory procedures, have significantly improved over the years. In the first year the grading scheme was often ambiguous since the laboratory involved many professors and teaching assistants. This has significantly improved in 2011, as a result of great effort of all involved lecturers on unifying criteria and laboratory preparation tests. Homework and tests have also been improved in the previous two years.

Since 2011, students tend to spend much more time preparing for exercises. This means that the goal of improving the significance of the laboratory course compared to theoretical courses is achieved.

The last three statements show the average results of all involved lecturers, without significant variation in individual marks. In general, students seem to be very enthusiastic with the lecturers.

In the last year a significant drop occurred in students' interest in the questionnaire. Since FER's statute allows only voluntarily student questionnaires, lecturers may only encourage,

Fig. 4. RES trainer.

but not mandate, students to take part in questionnaires. However, according to [23], students tend not to take the voluntary questionnaire if they are generally happy with the course.

B. Professional Feedback

The developed laboratory exercises were discussed with engineers working with the TSO, the Distribution System Operator (DSO), electricity generation companies, and consulting companies. Lack of renewable energy sources and smart grid concepts were identified as the biggest shortcoming of the laboratory. This initiated a further development which includes RES trainer and smart grid data acquisition system. The goal of the RES trainer is to introduce students to household RES systems, which are becoming ever more significant in power systems. On the other hand, data acquisition system is the first step towards implementation of efficient multi-energy systems of the future.

C. New Exercises

RES trainer, shown in Fig. 4, is conceived as a modular system which includes the following elements: renewable generation (85-W solar panel and 500-W wind turbine), storage device (battery) with charging regulator, power electronics (DC/AC converter), loads (AC and DC LED and halogen lamps, rheostat) and measuring instruments. Students will be able to perform the following experiments:

- measuring solar panel current-voltage characteristic;
- delivering electricity produced by the solar panel/wind turbine to the mains network;
- using solar panel and/or wind turbine to supply DC and AC loads;
- using a battery storage to shift RES generation to high loading time periods.

Since this exercise requires a clear weather, it is added to the syllabus at the end of the second semester and thus takes place in the late May.

The second exercise that has been developed is a system for acquisition of energy consumption data named Baltazar. Such system is a prerequisite for more efficient, reliable and responsive networks, commonly referred to as smart grids [24]. Accurate energy consumption measurements are required for implementation of the demand response (DR) schemes [25]. DR provides the ability to shift demand to less stressful time periods subject to consumer comfort. To determine comfort constraints, accurate measurements of the household hot water usage and indoor/outdoor temperatures are required. The energy management system (EMS) accumulates measurements to schedule appliances. Another feature of the EMS is alarming the user in case parameters exceed preset values. As an example, a sudden huge increase in water consumption indicates that the pipeline may be punctured.

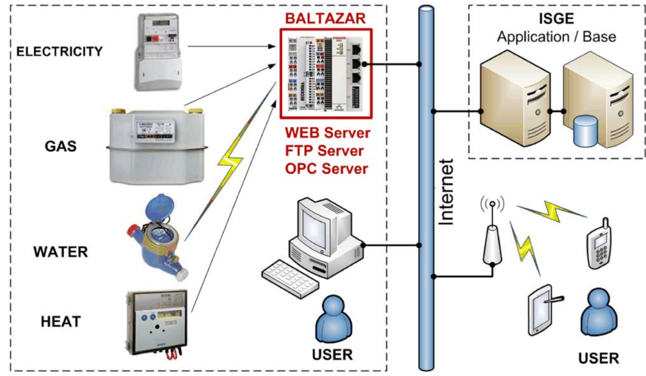

Fig. 5. Baltazar—system for acquisition of energy consumption data.

Baltazar is designed as a demo-panel equipped with electricity, gas, water and heating consumption meters linked to a modular system of programmable automatic controllers (PAC), as shown in Fig. 5. Information energy management software (IEMS) enables continuous energy and water consumption data acquisition, data analysis and data streaming to files. FTP can be initiated by IEMS (polling) or PAC hardware (pushing) which is achieved using FTP client/server architecture. The capacity of the compact flash memory is designed so data can be stored in PAC for two years. For real-time data view and history data view, a web server that communicates with user interface is used. The Object Linking and Embedding for Process Control (OPC) server enables alarming and supervisory system control by a smartphone or a tablet device. This exercise will be added to the syllabus at the beginning of the second semester.

VIII. Conclusions

Establishing a two-semester power system laboratory that encompasses practically all aspects of power system engineering is an ongoing challenge. Effective student feedback is needed to keep and expand positive aspects of the laboratory and to reduce the negative ones. Additionally, laboratory contents need to be reconciled with the industry needs, which calls for cooperation with industry experts. It is important for universities in general to have constant collaboration with industry, as this experience is priceless in setting up a power systems laboratory comparable to industrial ones.

Long-term laboratory updates are focused on adding renewable generation to the existing model of a power system described in Exercise 1. Adding a wind turbine to the existing hydro and thermal generators will enable investigating how asynchronous active power flows can help preserving the rotor angle stability of the system. Another experiment will investigate the impact of power electronics pertaining to installation of solar panels and/or wind turbines to the power system stability.

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