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Engineering education for smart grid systems in the quasi-industrial environment of the LINTE^2 laboratory

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ABSTRACT: Smart grid systems are revolutionising the electric power sector, integrating advanced technologies to enhance efficiency, reliability and sustainability. It is important for higher education to equip the prospective smart grid professional with the competencies enabling them to navigate through the related complexities and drive innovation. To achieve this, interdisciplinary education programmes are necessary, addressing *inter alia* integration of renewable energy sources, data analytics, AI and machine learning, cybersecurity, policies and regulatory frameworks. Hands-on experience, industrial training and research-based learning are also highly desirable components of such programmes. This article describes how Gdańsk University of Technology (Gdańsk Tech), Gdańsk, Poland, employs its unique Laboratory for Innovative Power Systems and Integration of Renewable Energy Sources (LINTE^2 Lab), to support comprehensive education in smart grids. Starting with simulation and virtualisation, students gradually extend their knowledge and competencies through project, research and challenge-based activities in the quasi-industrial environment of the LINTE^2 Lab.

Keywords: Engineering education, smart grid systems, challenge-based learning

INTRODUCTION

The evolution of electric power systems into smart grid systems represents a significant leap forward in the way people generate, distribute and consume electricity. Traditionally, power systems are operated on a one-way flow basis, with electricity generated at large centralised plants and distributed through a network of transmission and distribution lines. However, the emergence of renewable energy sources, advancements in digital technologies, and the growing demand for efficiency and sustainability have catalysed the transition towards smarter grids.

Smart grid systems exploit a combination of sensors, automation and advanced communication technologies to enhance reliability, efficiency and sustainability. These grids enable bidirectional flow of electricity, allowing for the integration of distributed energy resources, such as solar panels, wind turbines and energy storage systems. Moreover, they facilitate real-time monitoring and control of the grid, optimising operations, reducing downtime and minimising losses.

Furthermore, smart grid technologies empower consumers to actively participate in the energy ecosystem through features like smart meters and demand response programs. These tools enable consumers to monitor their energy usage in real-time, adjust consumption patterns to save costs during peak hours, and even contribute excess energy generated by renewable sources back to the grid. Overall, the evolution towards smart grid systems represents a transformative shift towards a more resilient, efficient and sustainable energy future.

As the landscape of electrical engineering evolves with advancements in smart grid systems, higher education institutions (HEIs) are compelled to enhance their curricula to meet the demands of this rapidly changing field [1][2]. One fundamental adaptation lies in the integration of courses specifically tailored to smart grid systems within the electrical engineering curriculum. HEIs are incorporating modules covering topics, such as power electronics, renewable energy integration, data analytics and cybersecurity, all of which are crucial components of modern smart grid systems. Another attitude is to foster interdisciplinary collaboration to provide students with a holistic understanding of smart grid systems [3][4].

In the Faculty of Electrical and Control Engineering at Gdańsk University of Technology (Gdańsk Tech), Gdańsk, Poland, the challenges of engineering education for smart grid systems have been addressed through the introduction of special collaborative student projects and activities. Their common features include a primary focus on hands-on experience, an interdisciplinary approach, and implementation within the quasi-industrial infrastructure of the Laboratory for Innovative Power Systems and Integration of Renewable Energy Sources (LINTE^2 Lab), which mimics many of the complexities of real-world smart grid systems. Tackling complex challenges in the field nurtures innovation and creativity among future electrical engineers, empowering them to make significant contributions to the advancement of smart grid technologies.

LINTE^2 LAB AT GDAŃSK TECH

The LINTE^2 Lab, established in 2016, represents a significant milestone in the infrastructure development of Gdańsk Tech, ranking among the most extensive infrastructural undertakings executed at the University within the last decade. The primary objective of the laboratory is to serve as a dedicated research hub that supports and expands research, development and innovation geared towards contemporary electrical power systems, with a particular emphasis on smart grids and renewable energy sources (RES).

At the heart of the laboratory lies its sophisticated research installation, which can be categorised into three principal components. First, the laboratory contains an array of functionally complete pieces of electrical equipment - dubbed *functional units* and featuring advanced digital control systems (Figure 1). There are currently 30 such units, including *inter alia* power generation units, transmission and distribution components, energy storage units and electric vehicle charging stations. Secondly, the laboratory boasts a complex remotely-controlled electrical switchgear, facilitating the configuration of all the devices into diverse power systems and networks, such as electrical microgrids, energy clusters and virtual power plants. And finally, the laboratory features a complex distributed control system, underpinned by an Ethernet communication network and interconnecting local controllers and intelligent electronic devices (IEDs) of all functional units under the supervisory control of a dedicated supervisory control and data acquisition (SCADA) system (Figure 2).

Figure 1: The main space of LINTE^2 Lab - an array of functional units and the main electrical switchgear (photograph by Piotr Niklas).

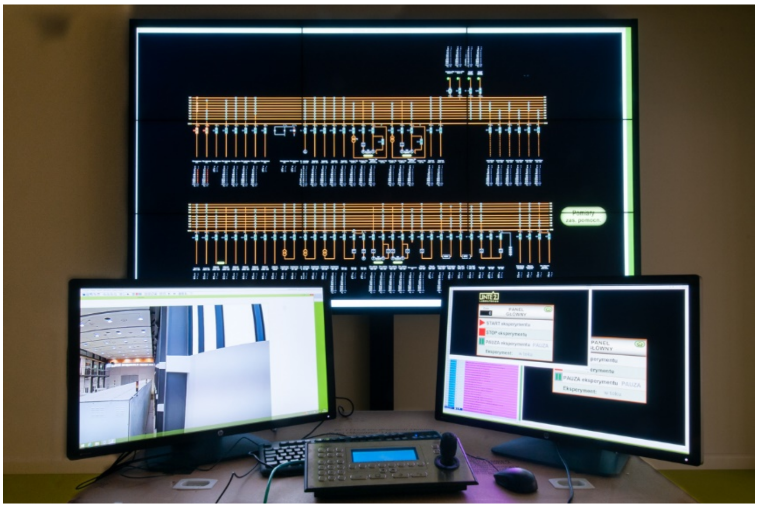

Figure 2: Lab's dedicated SCADA system - the core of distributed control system (photograph by Piotr Niklas).

The versatility of the installation allows the researchers of Gdańsk Tech to design, fine-tune and validate the cutting-edge technologies tailored to the needs of modern power systems. Through simulations, hardware-in-the-loop and real-time experiments, researchers are empowered to test and validate novel concepts and theories across a spectrum of domains. The infrastructure also serves as a place for exploring the complexities of real-time communication within distributed industrial automation systems. Its control system not only enables the investigation of real-time communication protocols but also facilitates the development and refinement of critical aspects of SCADA systems and human-machine interfaces.

In addition to its research relevance, the LINTE^2 Lab is often exploited in collaborative projects with industry stakeholders, hosts demonstration projects, and provides comprehensive training programmes. And last but not least, the laboratory is also used as an invaluable asset in engineering education. Its multifaceted equipment provides students with a hands-on learning environment, where they can investigate the complexities of modern power systems. Through practical exercises and simulations conducted within the laboratory, students can explore a variety of smart grid concepts in a very realistic test environment.

Moreover, the LINTE^2 Lab serves as a platform for fostering interdisciplinary collaboration and innovation among students. By being engaged in research projects and experimental studies within the laboratory, students from various engineering disciplines can work together to tackle complex challenges of smart grids. This collaborative approach not only enhances technical proficiency but also fosters critical thinking and problem-solving skills.

The research infrastructure of the LINTE^2 Lab has also been used in the implementation of numerous student diploma theses, student team projects, summer schools for domestic and foreign students, as well as technical support for doctoral students. Overall, the laboratory serves as a dynamic educational environment, where students can acquire the knowledge, skills and practical experience needed to excel in the field of smart grid engineering.

COLLABORATIVE STUDENT PROJECTS IN THE FIELD OF SMART GRIDS

The organisation of collaborative student projects in the Faculty of Electrical and Control Engineering at Gdańsk Tech follows a structured set of guidelines. These projects, undertaken as elective courses in the sixth semester of the undergraduate programme, involve a minimum of 18 students per group. Each group is divided into subgroups of up to six students, with each subgroup assigned to a distinct project. Projects are supervised by academic advisors who oversee their development and implementation execution (Figure 3).

Figure 3: Students of Gdańsk Tech executing a supervised team project in the LINTE^2 Lab. Pictured are (l-r): K. Kotkowski, M. Breza and F. Grabowski (image by courtesy of WAGO ELWAG).

Project proposals should be formulated according to the conceive, design, implement, operate (CDIO) guidelines [5] and may originate from academic staff, students or collaborating companies. The academic advisor of a proposed project is responsible for outlining its objectives, scope, schedule, task allocation, and potential sources of funding and resources. The proposals undergo evaluation by the Faculty’s Committee for Quality Assurance in Education.

Throughout the project, academic advisors provide oversight and mentoring, monitor progress, and assess students’ performance based on assigned tasks. Additionally, students must present the results of their projects at a faculty seminar. Successful completion of the project, along with participation in the seminar, is a prerequisite for passing the course. Importantly, projects undertaken as part of this course may serve as the basis for students’ engineering thesis projects, further integrating academic learning with practical applications in the field.

Every year several student projects are proposed to be implemented using various IEDs. Introducing IEDs into the educational curriculum for smart grid systems offers an interactive and hands-on approach to understanding the complexities of the electrical power sector. IEDs serve as an excellent tool for simulating real-world scenarios, allowing students to grasp fundamental concepts, such as communication protocols and cybersecurity measures within smart grid infrastructures [6][7]. Through practical exercises, students explore the intricacies of data exchange protocols like Modbus or DNP3, gaining insight into how information flows between various components of the grid.

One of the primary advantages of using IEDs is their versatility in emulating diverse smart grid functionalities. Students can simulate scenarios involving the Lab's functional units, all of which are essential components of modern smart grids. By programming IEDs to control and monitor these systems, students can develop a comprehensive understanding of how different elements interact within a smart grid environment, from generation to distribution and consumption.

Particularly, incorporating the IEC 61850 standard into IED-based educational activities further enhances students' understanding of communication protocols and interoperability within smart grid systems [8][9]. IEC 61850 establishes a common framework for the integration of various IEDs within substations, enabling seamless communication and interoperability across different vendor platforms. By familiarising students with this standard, educators can illustrate how IEDs facilitate the exchange of critical data and commands between substations, control centres and other components of the grid.

Through practical exercises involving IEC 61850-compliant devices and IEDs, students can explore the benefits of standardised communication protocols in enhancing the efficiency, reliability and cybersecurity of smart grid operations. They can simulate scenarios involving substation automation, fault detection and system monitoring, gaining first-hand experience in configuring IEDs to communicate using the generic object oriented substation event (GOOSE) messaging protocol and sampled values.

Moreover, integrating cybersecurity principles into IED-based exercises is crucial for preparing students to address the growing threats facing the electrical power sector. Through simulated cyberattacks and defence mechanisms, students can learn to identify vulnerabilities in grid systems and implement robust security measures to safeguard against potential breaches. Understanding the importance of encryption, authentication and intrusion detection within smart grid communications is essential for future specialists to ensure the reliability and resilience of electrical infrastructure.

Overall, incorporating IED-based projects into educational programmes for smart grids provides students with a practical and immersive learning experience. By engaging in hands-on activities that simulate real-world scenarios, students can develop the skills and knowledge necessary to design, operate and secure the next generation of intelligent power systems. This approach not only enhances technical proficiency but also fosters critical thinking and problem-solving abilities essential for addressing the evolving challenges of the electrical power sector in the digital age.

The most interesting illustrations of student projects implemented using this approach are: a controller for the supervision of MV/LV transformers in distributed networks with high penetration of PV, a controller for the integration of multi-protocol communication in a LV switchgear, a controller for power balancing of energy storage units connected to PV installations [10][11], a controller for an automatic transfer switch (ATS) in a multi-source LV switchgear (Figure 4), a controller for the supervision of DC breakers with electrical protection, supervision and communication functions using the IEC 61850 protocol. The latter project won the highly esteemed Siemens Award for Graduates of Automation and Robotics in the national student competition in 2020.

Figure 4: Students of Gdańsk Tech presenting the ATS system as a result of their project. Pictured are (l-r): R. Izbaner and J. Labudda (photograph by Andrzej Augusiak).

OTHER TECHNIQUES USED IN EDUCATION WITHIN THE LINTE^2 LAB

Despite the unique potential of the LINTE^2 Lab in rendering real-world environments, it is sometimes necessary to complement the hardware functional units with digital solutions, especially when practical experiences with real equipment are limited or impractical. One such technique is the digital twin approach, which employs power hardware in the loop (PHIL) technology and real-time simulation (RTS) to replicate the behaviour of selected power system components. By utilising diverse models and algorithms, this approach allows the emulation of various scenarios, including faulty operations, thereby providing invaluable insights into power system control strategies [12].

In this context, using tools like Stateflow, Simscape and Simulink Real-Time from MathWorks can greatly enhance the learning experience. Stateflow enables the modelling and simulation of complex control logic, allowing students to design and analyse intricate system behaviours, such as those found in smart grid components. Simscape facilitates the development of multidomain physical models, enabling students to explore the interactions between electrical, mechanical, thermal and other systems within the smart grid environment. By integrating these tools with Simulink Real-Time, which enables real-time simulation and testing, students can bridge the gap between theoretical concepts and practical implementation. Moreover, the use of these tools fosters critical thinking and problem-solving skills, equipping students with the necessary expertise to tackle real-world engineering challenges in the field of smart grid development.

A good example of such a project is the development of an electronic on-load tap changer for power transformers. The equipment will play a crucial role in voltage regulation within the power grid, particularly with the increasing power generation from renewable sources. That project spanned two academic years and provided students with hands-on experience throughout the entire R&D process: from idea conception, through testing and verification by simulation, to prototyping and experimentation within the quasi-industrial environment of the Lab.

This multidisciplinary undertaking demanded knowledge across various fields, including electrical engineering, materials science, power electronics, control theory, machinery diagnostics and computer programming. Throughout the project, various switching modes of thyristor taps were designed, manufactured and tested, culminating in the development and implementation of an algorithm for short-circuit-free tap changing using a field-programmable gate array (FPGA) with an integrated processor [13].

Owing to its educational capacity, the LINTE^2 Lab attracts considerable interest from students of many HEIs co-operating with Gdańsk Tech, both domestically and internationally. An interesting example of using the LINTE^2 infrastructure in this context was the collaboration of Gdańsk Tech with Florida Gulf Coast University (FGCU) in the USA. In 2020, the universities carried out real-time transatlantic classes with FGCU students controlling the LINTE^2 resources from their laptops.

The experiment involved the control of a physical distribution microgrid set up in the LINTE^2. Students from the USA had the opportunity to gain insight into the operation of a professional SCADA system dedicated to smart grids. This collaboration exemplified and proved the potential of highly digitised infrastructures such as the LINTE^2 to serve students and researchers at geographically distant locations.

CONCLUDING REMARKS

Preparing specialists for the dynamically developing field of smart grids requires transition from traditional to enhanced engineering education. The traditional approach tends to be based on moderately integrated sessions of lecturing, tutoring and laboratory activities and very often priorities theoretical knowledge over practical application. This leads to a gap between academic learning and real-world challenges. Smart grid technologies demand multidisciplinary skills that extend beyond textbook theories, necessitating a shift towards enhanced education methodologies with wide use of hands-on experience in realistic environments.

With the unique opportunities provided by the quasi-industrial infrastructure of the LINTE^2 Lab, Gdańsk Tech offers its students practical insight into the complexities of smart grids. The article describes the experiential learning approach, primarily implemented in the form of collaborative projects, which enables students to bridge the gap between theory and practice. This approach allows future engineers to gain a deeper understanding of concepts, such as renewable energy integration, grid optimisation and cybersecurity.

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BIOGRAPHIES

Andrzej Augusiak, PhD, is an associate professor at the Faculty of Electrical and Control Engineering at Gdańsk University of Technology (Gdańsk Tech), Gdańsk, Poland. He performed as the main project co-ordinator for the development of the Laboratory for Innovative Power Systems and Integration of Renewable Energy Sources (LINTE^2 Lab). Currently, he holds the position of Vice Head of the LINTE^2 Lab and is responsible for the LINTE^2 Lab's operational management and R&D services for industrial companies. His research and teaching interests include energy conversion technologies, renewable energy sources and communication protocols in smart grid environments.

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Janusz Nieznański received his MSc, PhD and DSc (doctor habilitatus) degrees in electrical engineering from Gdańsk University of Technology (Gdańsk Tech), Gdańsk, Poland, in 1981, 1990 and 1999, respectively. Since 1982, he has been with Gdańsk Tech, where he held the positions of Vice-Dean and Dean of the Faculty of Electrical and Control Engineering, and is currently a Full Professor and Vice-Rector for Internationalisation and Innovation. He was a Visiting Professor with the French higher education institutions: the Institut National Polytechnique de Toulouse, in 2001, the Ecole Centrale de Lille, in 2005 and 2006, and a Visiting Researcher at the R&D Centre of Alstom Transport SA, Semeac, France, in 2006 and 2007. He has authored or co-authored about 130 scientific and technical papers and was the project leader in many national and international research projects. His research and teaching interests include control, diagnostics, modelling and simulation of power electronic converters and electrical drives, digital signal processing for power electronic applications, digital frequency synthesis and vibroacoustics of inverter-fed AC machines.