JURAJ HAVELKA   ANTE MARUŠIĆ   IGOR KUZLE HRVOJE PANDŽIĆ TOMISLAV CAPUDER

juraj.havelka@fer.hr   ante.marusic2@fer.hr   igor.kuzle@fer.hr hrvoje.pandzic @fer.hr tomislav.capuder@fer.hr

University of Zagreb Faculty of Electrical Engineering and Computing

HANDS-ON EXPERIENCE WITH POWER SYSTEMS LABORATORY UPGRADE

SUMMARY

This paper addresses the challenges of developing a modern power system laboratory at the Faculty of Electrical Engineering and Computing, University of Zagreb. Focused on problem-based learning, the laboratory, developed together by professors and students, is a key to practical teaching of power system design, analysis and control.

Key words: Power system laboratory, power system design, SCADA, intuitive demonstration, laboratory education.

1.   INTRODUCTION

The Zagreb University Faculty of Electrical Engineering and Computing, with its 5000 currently enrolled students, offers BSc MSc and PhD degrees in field of

Electrical Engineering and Computing. At all three academic levels, the Department of Power Systems has approximately 500 students.

In the training laboratory for Power Systems at the Department of Power Systems, the practical classes of the courses Electrical Power Plants [1], Dynamics and Control of Power Systems [2] and Distribution Systems are carried out and lectured on. The purpose of practical classes and training is to enable the students to master the needed practical skills in controlled environment. Besides, the Laboratory also provides the possibility of performing various types of experiments that would otherwise be either too expensive or practically almost impossible to carry out in real electrical power systems [3]. The Laboratory consists of the following plant models: hydroelectric and thermal power plants that can operate in parallel; power system network; power loads; and substation with circuit breakers, feeder disconnectors, busbars and a number of transformers. Due to the size of the Laboratory (200 m²) and shortage of finances the Laboratory has been poorly maintained during the past years and is therefore rather outmoded. Hence the efforts have been put into the fund raising for its modernization and purchasing the essential equipment; at the same time part of the equipment was donated by sponsors. Few younger professors engaged students into revitalizing the laboratory.

2.   GENERAL INFORMATION

The Laboratory is conceived as a miniature electrical power system (Fig. 1 and 2) that consists of the following:

- The model of thermal power plant (E1) with primary equipment: the motor simulating thermal turbine, generator, generator busbars, generator circuit breaker and feeder disconnector (serving to connect with the Faculty power system); and secondary equipment: measuring current and voltage transformers, protective relays, and power plant control system, including also the network synchroscope.
- The model of run-of-river hydro power plant (E2) with a Pelton turbine (Qn=27 l/s). At the level beneath the hydroelectric power station there is a 7000 liter water reservoir and a pump that pumps the water into the pipe leading to the turbine, thus simulating the penstock (simulated head is 60m). The hydroelectric power plant is equipped similar to the thermal power plant regarding the primary and secondary equipment. In addition to that, the important elements in this power plant are the automatic voltage regulator and the automatic generator control governor [4], [5].
- The rigid network (busbar E3) is the real external electric power network, which the two power plant models can be synchronized with; this enables the students to see the operation of the model power plant in the Croatian electric power system.
- Transformer substation with three winding transformer to which the loads can be connected. The transformer substation is fully equipped

with circuit breakers, feeder disconnectors, measuring current and voltage transformers, protection devices and control circuits.

- Different types of loads connected to power system model. These can be active and reactive (inductive and capacitive) loads, or their various combinations. They are used for simulation the dynamic operation of power plants and for changing the power plant parameters depending on connections of different types of loads [6].

The model of high voltage substation; it is discussed in further text.

A series of main lines models with circuit breakers and feeder disconnectors simulating a high voltage power system network that can be connected with or disconnected from the mentioned objects in different combinations.
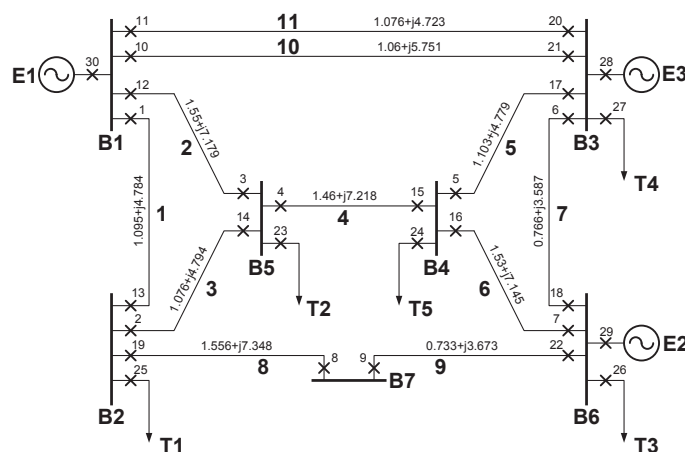

Figure 1. Part of power system laboratory

Figure 2. Part of power system laboratory

The conception of power system laboratory is based on real Croatian power system where approximately 50% of power is produced in hydro power plants and the other 50 % in thermal power plants.

3.   THE PROBLEM

The traditional construction of Laboratory, with no means of communication between single elements, provided challenge in its reconstruction. There was a need to equip laboratory with the most recent technologies and modern solutions used in everyday practice [7] so the students could gain the maximum benefit from practical classes. In order to improve the situation, decision was made to find the appropriate model of financing the reconstruction of the Laboratory supported by the entire Department of Power Systems staff. The very concept of the Laboratory has not been changed for it is general opinion that the model of power system is equally interesting and needed as before, today even more, since in this way the students gain the necessary practical knowledge about how the system operates.

The financing model is a topic per se, and it will not be discussed in detail. Suffice it to say that it has been agreed upon with the industrial companies interested in collaboration with our Department.

As for the new elements, the building of another thermal power plant and renewal energy sources has been planned. Besides, when all the legal requirements are satisfied, the State authorities will be asked for permission to authorize the Laboratory to test and issue certificates of operation for relay protection devices.

The reconstruction began with the simplest part: one line bay of substation. These activities have been fully completed and will be focused upon in our paper. The hydro power plant is currently being reconstructed in terms of full automation, from voltage and speed governor, various measurements, digital protection relays to automatic synchronization with the rest of electrical power system [8].

It should also be pointed out that the reconstruction of the Laboratory is designed in terms of full automation of all objects and remote control by OPC technology [9], [10]. Hence, the final objective is to design the central SCADA system for complete control of the Laboratory and to enable all those who are interested in these activities to follow up the operation of laboratory elements via the Faculty intranet [11] enabling distant learning for students. The idea is to inform all those who are interested in our activities about the reconstruction of the Laboratory, our experiences, and final outcomes. At the same time all the suggestions and ideas of those with similar experiences are highly welcomed.

4.   RECONSTRUCTION OF THE SUBSTATION MODEL

The model one line bay of substation has been designed in order for the students to learn how to correctly manipulate circuit breakers and feeder disconnectors in the substation [3], [12]. The major problem when dealing with the one line bay is that the feeder disonnectors do not serve to break the power circuits and should not be used for that purpose, since the circuit breakers are meant for that. However, for the more complex configuration of the substation the greater is the probability that someone might press the wrong button and instead of using the circuit breakers the power circuit is broken by feeder disconnector. It is indeed the model of a simple substation that has been installed in our Laboratory that clearly shows the mode of feeder disconnector blockage to prevent the undesired manipulation in substation and therefore possible unwanted power circuit breaking with feeder disconnector.

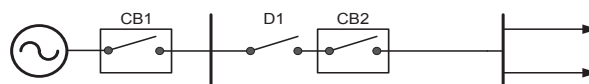A single line scheme of the substation is shown in Fig. 3 (it is a three-phase system).

Figure 3. Single line scheme of substation, simple configuration

The substation is supplied on one side only, while on the other side there are output lines for loads. The mode of the feeder disconnectors blockage is explained to the students by using a simple substation configuration (Fig. 3), while as a task they are given a complex configuration (Fig. 4) so they can themselves produce the blockage of disconnectors.
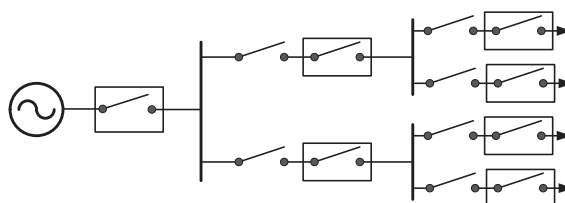

Figure 4. Single line scheme of substation, complex configuration

Before the reconstruction of Laboratory began, the practical classes were carried out on the model of substation (Fig. 5 and 6) of a rather simple configuration (Fig. 3).
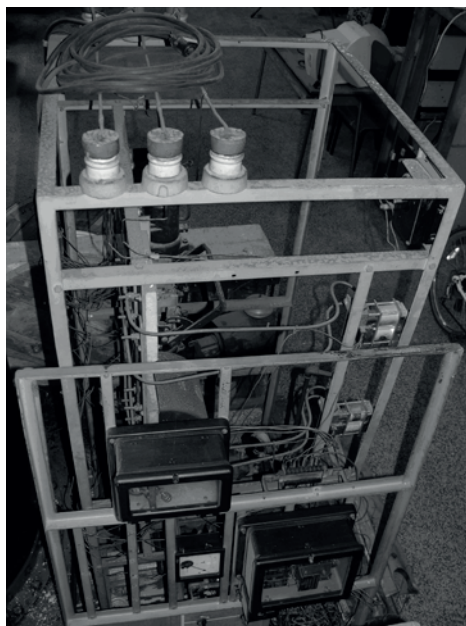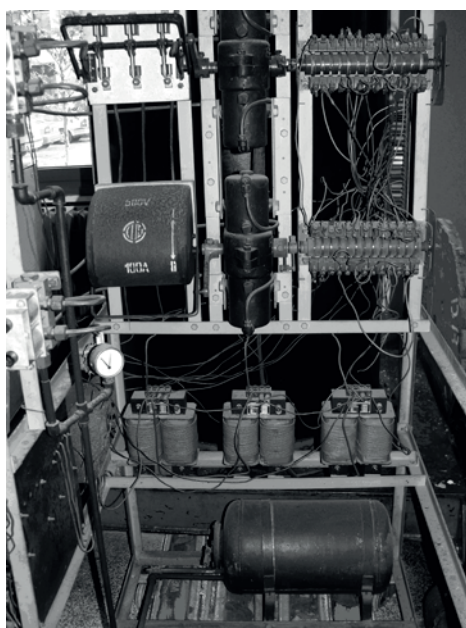
Figure 5. Part of old substation – busbars

Figure 6. . Part of substation – feeder disconnector(1), circuit breaker(2) and transformers(3)

The mere view at the above figures is sufficient without any comment as to the need for laboratory reconstruction. Fig. 5 clearly shows three busbars on top of the model high voltage substation to which the cables lead down to the feeder disconnector, shown in Fig. 6, leading to the circuit breaker and current transformers (three transformers at the bottom of the Fig. 5). At the bottom, as shown on Fig. 6, there is also a pressurized air container connected with a compressor that maintains constant pressure. It served as a system of compressed

air which was used to control the circuit breaker and the feeder disconnector. The control buttons were connected to the pneumatic system. The control push buttons and mode of feeder disconnector blockage are shown in Fig. 7.
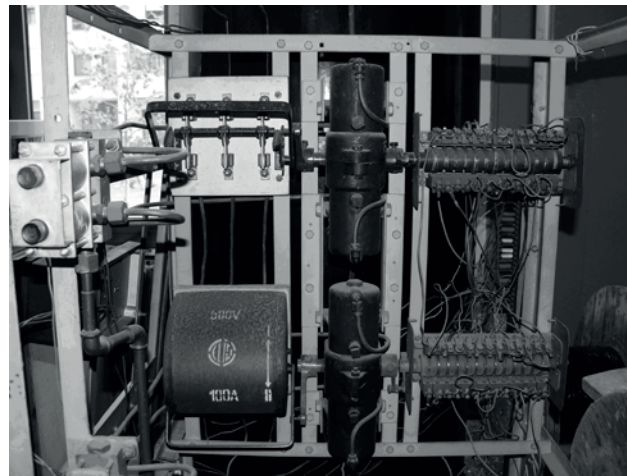

Figure 7. Control buttons(1) and blockage logic(2) in old substation

The wires and conductor rings, visible on the right side of the Fig. 7, were the logic that served to block the feeder disconnector and circuit breaker, i.e. they responded to a simple question of whether the disconnector should be blocked or not [13]. The operating principle was in that the conductor rings were mechanically connected to the disconnector and circuit breaker, while they were inter-connected with wires and electrical circuits of the control push buttons. Depending on the conductor rings position, determined by the position of circuit breaker and feeder disconnector, the electrical circuit of the control push button was either open or closed. When the feeder disconnector control circuit was open it was not possible to operate the disconnector with push buttons and it was blocked. Reversely, when the circuit breaker was open control circuit was closed, by pushing the control button it was possible to operate the disconnector which then was not blocked.

The objective of practical class was to show the students how to prevent the operating staff in a substation to erroneously manipulate the disconnectors and circuit breakers [3], [12]. The described model was severely outdated, i.e. such a mode of blockage is no longer applied in modern plants [7], [23]. There was also a danger of causing injuries to students by electric shock. Other shortcomings were absence of complete measurement of currents, voltages and other parameters, and the inability to communicate with the other substation elements (no possibility of remote control), which resulted in the fact that it was not compliable with the SCADA system.

These are the principal reasons why modernization of the Laboratory was urgently needed. The Fig. 8 and Fig. 9 show the new model of substation.
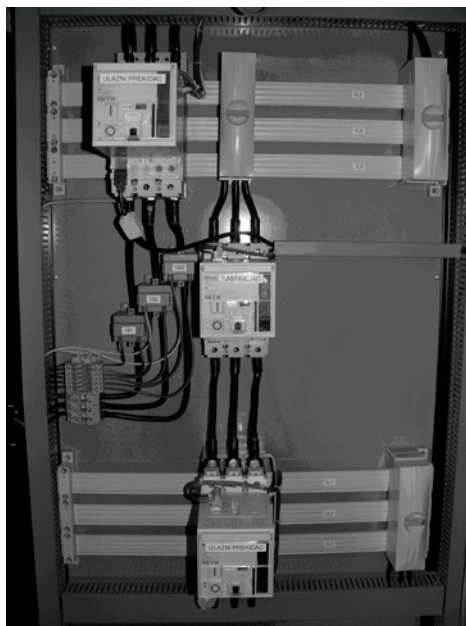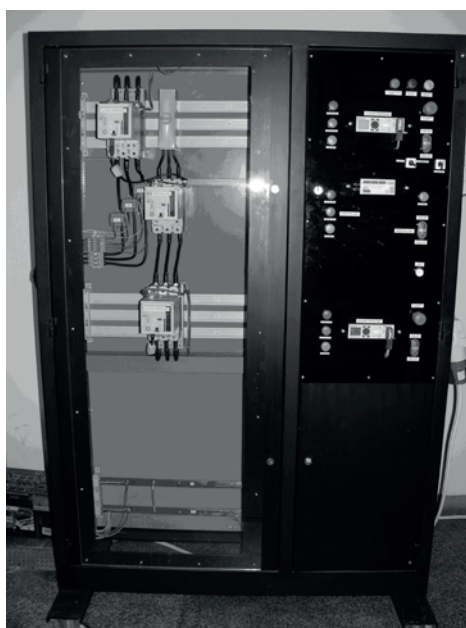
Figure 8. Model of high voltage segment

Figure 9. Model of new substation with high voltage segment and control and automation segment

It is divided (realized) into two segments. The left segment contains the model of one line bay, while the control segment with the movable control board is located on the right (Fig. 9). Since the device serves for the simulation of a high voltage plant, the model is realized by using the low voltage equipment; a careful view of Fig. 8 reveals that there is no return line, but only the three phases. Of course, there is a return line, only it is hidden so that the students can get better idea of the high voltage plant. Naturally, they are told that this is only the model

plant, while upon completion of practical class they are shown the real 10 kilovolt transformer substation that supplies the Faculty and is located within it, so that they can see the real circuit breakers, disconnectors, busbars and transformers. The developed model does not clearly differentiate the feeder disconnector from the circuit breaker as they are almost identical in appearance (using the same hardware); this is not the case in real substation, since the disconnector serves to the safety of the staff and it visibly separates the part of the plant under voltage from the voltage free segment. The students are informed about these facts in due time.

The controlling of the circuit breakers and disconnectors is simple and is performed in two ways: local - by push buttons located in the model substation, or remote - by computer serving as remote control station. If push buttons on the model are used then manual, or local, operation is employed and it is adjusted on the model itself by rotary cam switch. When automatic operation is desired (SCADA computer program) the rotary cam switch on the model should be turned from manual to automatic operation mode. The purpose is to show the students how safety at work is ensured in the substation [14] since, if it were not the case, the remote control would be possible even if some of the staff are present in the substation, which could be a life threatening situation.

The blockage of disconnector is designed in two ways. Fig. 10 shows the right segment of the model containing the control logic and automation. The first blockage mode refers to control by push buttons on the control board. This is achieved through a series of relays located at the bottom of the model, as shown in Fig. 10.
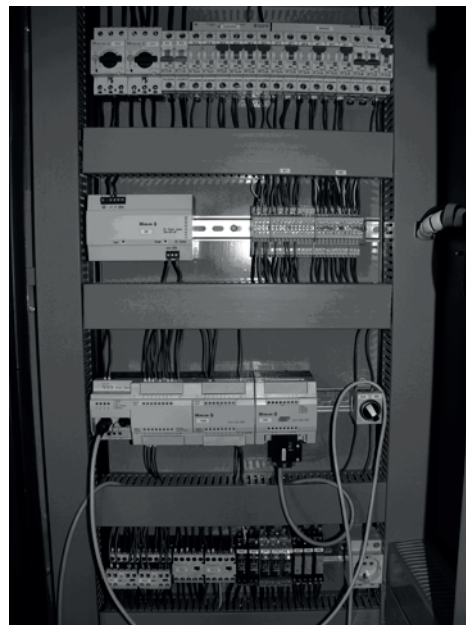

Figure 10. Relays used for disconnector blockage

They are connected with auxiliary contacts from the circuit breakers and disconnectors, which also pass across the control push buttons, allowing or not the control of the disconnectors. The relays are adjusted in the way that if the breaker 2 (Fig 3) is on, it prevents the control of disconnector 1 in a way that the electrical circuit on the push buttons for disconnector control remains open. If the breaker 1 opens then the relays close the control circuit that passes across the control push buttons for disconnector and its control is possible. In the same way functions the blockage of the mentioned disconnector if the circuit breaker no. 2 and the disconnector are open. The blockage serves to prevent the disconnector to be switched on if the breaker no. 2 is closed. If there were no blockage there would be the possibility of user connecting to the power system through the disconnector, which is not allowed.

The students learn when and how to employ blockage of the disconnector by analyzing all combinations.

Although in practice another type of blockage procedure is currently used [7], the students are shown the one using relays in order for them to learn more about the mode of blockage itself. As shown in Fig. 10, the other mode of blockage is designed by using the PLC. On its right side there is rotary cam switch which enables the selection of the desired mode of blockage: either by relays or by PLC. There is also a possibility of using both blockages simultaneously (the rotary cam switch is in neutral position). The PLC communicates with circuit breakers and disconnectors by auxiliary contacts. Every disconnector and circuit breaker has its own communication module that is connected with PLC and sends data on circuit breaker and disconnector faults and other conditions concerning the diagnostics.

A PLC contains software solutions for blockage of any disconnector. Through the serial connection the PLC is connected to the computer with SCADA software for controlling circuit breakers and disconnectors. If the software does not allow for manipulation with a certain disconnector, it is then impossible to open the desired UI in SCADA meant for controlling the given disconnector. In case of the program error in terms of possibility to open UI for control of a blocked disconnector, it is still not possible to perform control for the PLC would not allow it; during such effort the modal screen of SCADA system appears on display informing the user that at the moment it is not possible to control the disconnector and which actions should be undertaken to make it possible. It is important to know that the SCADA system for this substation model is designed by OPC technology [9], [10].
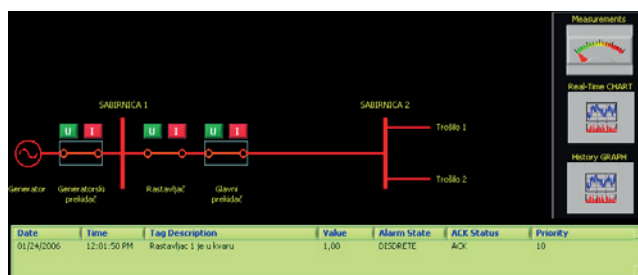

Figure 11. Single line diagram in SCADA system

Fig. 11 shows a single line diagram (from SCADA software) of the substation which can be computer controlled by the students (simpler configuration from Fig. 3). Parts of the substation without voltage are denoted by green color while the red ones have voltage. If there is a fault in either the disconnector or the circuit breaker it blinks yellow and the alarm appears in table shown in Fig. 10 informing about the type of fault, time of its occurrence and its site (with all additional information about whether the alarm is confirmed, who has confirmed it, whether it has passed, etc.).

The students can themselves design a single line diagram for control of the configuration shown in Fig. 4 [15]. They themselves program the logic for disconnectors blockage and can check on the substation the efficacy of their programs without fear of destroying the substation and the equipment. If the student is not yet capable of programming the PLC, the software support can be designed to block the disconnectors on the computer, and then the PLC serves only as interface for collecting data from the substation and sending data to the substation from computer [16], [17]. Following data analysis, based on the program designed by the student, the computer sends command via the OPC server to the PLC.

In the substation various measurements are also performed so that the voltage, current and power in the substation can readily be seen. The measurements are made by employing voltage and current measuring transformers that are connected to digital multimeter instrument that measures and calculates all essential values (phase currents, phase and line voltages, active power, reactive power, total power per phase, sum of all powers, frequency, total harmonic distortion, etc.) [18]. The instrument is located in the center of the control board and is shown in Fig. 12. In this way the students can see at the very site the values of various substation parameters in real time.
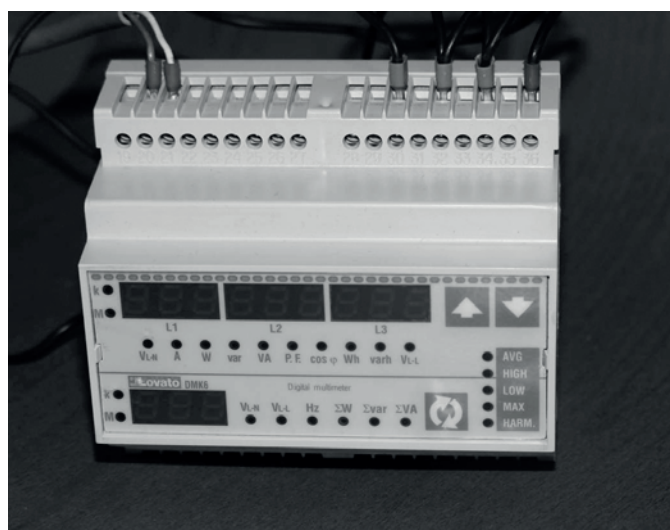

Figure 12. Digital multimeter on control board

A driver has been written for the multimeter instrument that enables communication between PLC and the instrument, by which all the measured values are automatically available to the PLC linked with the central computer. Hence the SCADA program does not serve only to control the plant, but to collect all the measured values into the database so that they can be reviewed by SCADA interface and reports made for the desired time periods if wanted (Fig. 13).
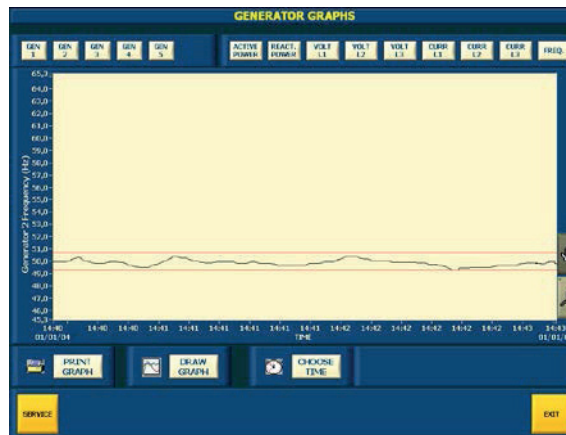

Figure 13. History viewer

With the multimeter on site it is also possible to see the real time values of all substation measured parameters remotely in the same SCADA system. Fig 14 shows UI programmed for that purpose.

Figure 14. UI showing measured real-time values and control buttons

In this way the students get the overall view of measurements in the substation, both the real time measurements and the historical measurements and therefore historical values of all measured signals as well.

It should also be pointed out that the technology of the SCADA system is entirely based on OPC technology, while the database is ODBC compatible [19], which enables the access to all data via the local network or the internet. Provided the needed licenses are obtained the students can perform certain experiments from their homes as well.

5. EDUCATION

Educational approach in practical classes consists of three key elements [20]. First, the practical class is organized to discuss one topic only. Second, theory lectures focus on a given practical class topic in a way that discusses the details relevant to successful completion of a given topic only. Third, following both, the theory and practical classes, a visit is organized to the real substation where the substation staff demonstrate all that the students have learned during theory lectures and practical classes (laboratory environment). In this way close connection is achieved between the theoretical part (lectures), practical classes (laboratory), and real world application (visit to the substation). Such an approach ensures the students' great interest in the curriculum and contributes to more comprehensive knowledge about the course.

5.1. Lecture

Theoretical lectures covering each practical class take 4 teaching hours weekly. During the lectures the students are given explanations on substation and its functioning [3], [21]. Further explanations are given on the construction blueprints of a substation, automation and SCADA system implementation together with proper management and operation of the substation [12]. When discussing the operation and management of the substation special emphasis is given to proper operation with the disconnectors and circuit breakers in the manner in which blockage of disconnector is made with the PLC and SCADA system. The principal objective of theoretical lectures is to enable the students to understand, at a theoretical level so far, the methods of construction planning, operation and management of the substation.

5.2. Laboratory classes

The laboratory classes consist of three parts, or sections. The first two sections

take place in one day, while the third one is conceived as a homework, which the students should complete by the end of the week.

1) The fist part is a demonstration class during which the students are presented with the elements of substation model and are given explanations on the methods of selecting the elements during the planning of substation construction, their purpose and how each single element works. Then the operation of substation is demonstrated, starting with proper management in order to prevent life threats, working with the circuit breakers and disconnectors locally and remotely with SCADA system, and current, voltage and power measurements are also demonstrated locally and remotely. During the final part of demonstration class the students are shown how various reports are made about the measurements in certain time periods and other reports, like e.g. alarm and event reports. A special point during the demonstration class refers to simulation of certain faults, for instance busbar short circuit and circuit breakers failures [3]. In this way the students obtain an overall picture about the substation.

2) The second part is for the students to independently design a disconnector blockage by PLC for a simple substation configuration (fig. 3). After the computer program is designed, it is tested on a substation model to find out whether it is appropriate or not. Since it is all about the substation model there is not danger for the students or the equipment in case of error in computer programming. Following the testing and corrections, if any is needed, the students control the operation of the substation locally and remotely; the control consists of the voltage, current and power measurements and of manipulation with disconnectors and circuit breakers. At the end the students make reports of events and failures in the substation and reports about measurements in given time periods in which different electrical power users were connected to or disconnected from the substation. This part of laboratory classes enables the students to gain practical knowledge based on lecture classes and on the first part of the laboratory classes.

3) The third part consists of the homework during which the students should independently design the SCADA control system for circuit breakers and disconnectors and for the measurement of electrical values. The SCADA system is designed for the complex configuration (fig. 4). Following the computer program design, the students get remotely connected to the substation and can thus check whether the program has been properly designed. This is the final part of laboratory classes during which the students are enabled to independently apply their theoretical knowledge and the knowledge gained during the first and second parts of laboratory classes. While the second section is mostly focused on team work, the third one emphasizes independent action, which is often the case in some key events in real world.

5.3. Real worldapplication

Upon completion of theoretical and laboratory classes, the students go to a one-day visit to real high voltage substation where the staff show them how it works, similar to laboratory environment, only now it is not a model substation but rather a real world one. In this way the connection is achieved between the theory,

the model, and the real world. Hence the students obtain a complete picture of the substation and are able to link the knowledge gained so far as a whole.

6. CONCLUSION

The new model of substation gives the students a significantly greater opportunity to get the idea of its functioning than the previous model does, starting from the possibility of one's own programming various types of disconnector blockages, depending on the substation configuration, either by relays or PLC, or a personal computer. The students are able to change configuration of substation from a simple one toward a more complex one and vice versa. The possibility of parameter measurements and their changes depending on supply, load and condition of the substation, provides the detailed insight into the situation of real high voltage substation. The developed model enables quite a number of experiments to be conducted in controlled conditions and without any danger to the students and the plant, which would otherwise not be possible in a real high voltage substation. The examples of experiments are: inducing a three-phase short circuit on a generator terminals in thermal power station, performed on the model of thermal power station in our Laboratory, and then the analysis of the electrical plant events by the recorded waveforms of current, voltage, excitation and speed of turbine rotation prior to the fault, at the moment of fault, and after the fault. The simulation power plant is equipped with digital protective relays, enabling the analysis of their trip depending on adjustments, and coordination with other protective relays. This is only one of the many experiments that can be performed in laboratory settings.

The major difference between the previous and the current model, beside appearance and complete automation, is the possibility of communication with the substation by OPC technology. This is indeed what makes it possible for the students to program their own system and compare it with the existing SCADA one, in order to gain the feeling what this is all about. It should also be emphasized that the plant can be controlled via the network. Finally, but not the least important, the use of OPC technology enables the link between this plant and the entire laboratory supervisory control and data acquisition system (also based on OPC technology), when our Laboratory will be completely reconstructed. This means that any additional element is a modular one, making it possible to add new elements or change the old ones without interfering with the functional baseline.

7. ACKNOWLEDGEMENT

8. REFERENCES

[1]   I. Kuzle, J. Havelka, H. Pandžić, T. Capuder, Hands-On Laboratory Course for Future Power System Experts, IEEE Transactions on Power Systems, vol. 29, no. 4, July 2014, pp. 1963-1971

[2]   I. Kuzle, K. Jurković, H. Pandžić, Development of the Power System Simulations Laboratory (in Croatian), 12. HRO CIGRE Session, Šibenik, November 08-11,2015, C6-06, pp. 1-7

[3]   H. Požar, High Voltage Substations, 4th ed., Zagreb, Croatia, Tehnička Knjiga, 1984

[4]   F. H. Raven, Automatic Control Engineering, 5th ed., New York, McGraw-Hill, 1995.

[5]   N. Kehtarnavaz, Real-Time Digital Signal Processing, Burlington, MA, 2005

[6]   V. Venikov, Transient Processes in Electrical Power Systems, 5th ed., Moscow, Mir Publishers, 1980

[7]   N. Srb, A. Torre, B. Kosorčić, Zbirka propisa za polaganje stručnog ispita iz elektrotehničke struke: Tehnička regulativa, Zagreb, Croatia, Electrotechnical Society Zagreb, 2007.

[8]   R. Wolf, Osnove električnih strojeva, 4th ed., Zagreb, Croatia, Školska Knjiga, 1995.

[9]   F. Iwanitz, J. Lange, OLE for Process Control: Fundamentals Implementation and Application, Hüthig Verlag Heidelberg, 2001.

[10]   OPC Foundation documents, Available: http://www.opcfoundation.org/Downloads.aspx?CM=1&CN=KEY&CI=283

[11]   J. Travis, Internet Applications in LabVIEW, Upper Saddle River, NJ, Prentice Hall PTR, 2000.

[12]   R. W. Smeaton, W. H. Ubert, Switchgear and Control Handbook, 3rd ed., McGraw-Hill, New York, 1998.

[13]   V. Pinter, Osnove elektrotehnike (Electric Circuits), vol. 2, 4th ed., Zagreb, Croatia, Tehnička Knjiga, 1987.

[14]   N. Srb, A. Torre, B. Kosorčić, "Zbirka propisa za polaganje stručnog ispita iz elektrotehničke struke: Regulativa zaštite osoba, okoliša, materijalnih i kulturnih dobara", Zagreb, Croatia, Electrotechnical Society Zagreb, 2007.

[15]   D. J. Ritter, LabVIEW GUI Essential Techniques, New York, McGraw-Hill, 2002.

[16]   J. Travis, J. Kring, LabVIEW for Everyone, 3rd ed. Upper Saddle River, NJ, Prentice Hall PTR, 2006.

[17] G. W. Johnson, LabVIEW Graphical Programming, 2nd ed., New York, McGraw-Hill, 1997.

[18] V. Bego, Mjerenja u elektrotehnici (Electrical Measurements), Zagreb, Croatia, Tehnička Knjiga, 2003.

[19] R. M. Riordan, Microsoft ADO.NET 2.0 Step by Step, Microsoft Press, Redmond, Washington, 2006.

[20] L. G. Huettel *et al.*, Fundamentals of ECE: A Rigorous, Integrated Introduction to Electrical and Computer Engineering, IEEE Transactions on Education, vol. 50, no. 3, August 2007, pp. 174-181

[21] L. L. Grisby *et al.*, The Electric Power Engineering Handbook, CRC Press in cooperation with IEEE Press, Boca Raton, FL, 2001.