An Interactive Educational Tool for the Teaching of Manoeuvres in Electrical Substations

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ABSTRACT: The philosophy of safety at work is one of the bases for the operation of electrical installations, with particular relevance in the manoeuvres in electrical substations. The curriculum for Electrical Engineering students should include such knowledge. This article presents an educational tool currently in use, which has demonstrated its full effectiveness in achieving the implementation of safe working methods in the planning and execution of manoeuvres in electrical substations. Comput Appl Eng Educ; View this article online at wileyonlinelibrary.com/journal/cae; DOI 10.1002/cae.20567

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INTRODUCTION

Today's engineers must not only adapt to changing environments, engage in lifelong training to maintain their technical skills and knowledge, and work effectively in a team, but they must also have knowledge of the business, social, and environmental impacts of their work. In Europe, for instance, a large number of countries are currently modifying both the structure and scope of higher education curricula, including engineering, to satisfy the requirements of the Bologna agreement [1].

The majority of Electrical Engineering curriculum of most final-year undergraduate students features a course based on medium/high voltage substations, which is principally focused on calculation and design [2]. However, it is customary for an engineer to be responsible for a working group devoted to maintenance work or to conducting manoeuvres. Given that such tasks involve an element of risk in their implementation both for facilities and, above all, for people who carry them out, it is important that, during their training, students acquire knowledge and awareness of the need to perform systematic procedures safely at all levels. This undertaking has been in effect for many years in the Department of Electrical Engineering of the University of Seville.

Traditionally, manoeuvres are explained through the use of the blackboard, which incurs limitations that render it an inefficient method of teaching. This inefficiency has led to the design of an interactive tool for the effective training in manoeuvres in medium/high voltage substations, which satisfies the Bologna requirements [3,4].

From an educational point of view, it is crucial that students not only learn the correct way to perform the manoeuvres, but that they also understand the consequences for people and facilities when errors occur in the execution of the manoeuvres. Great care has been taken in designing the tool so that the result of any error is reinforced upon the student, thereby very effectively underlining the importance of proper procedure.

The new interactive educational tool has been prepared in CodeSys environment, which is available in the download section of Ref. 5. On the other hand, the file of the educational tool will be available from the website of the Electrical Engineering Department of the University of Seville [6]. This educational tool is being successfully used in the classroom at the University of Seville, and the authors hope that it will soon be used in other Universities.

The acceptance and efficacy of this tool have been confirmed by means of evaluation questionnaires, personal interviews, and examinations, all of which reveal the potential of the proposed experimental setup to duly complement the theoretical matters and motivate students.

The rest of the article is organized as follows. In second and third sections, a brief description of manoeuvres in electrical substations is carried out. In the fourth section, the one-line system used in the article is described. The educational tool is

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presented in the fifth section. The educational development experience and the evaluation results are presented in sixth and seventh sections. Finally, in the eighth section, conclusions are drawn.

BACKGROUND THEORY

Manoeuvres are voluntary operations leading to a change of state of the system or equipment through the opening or closing of the corresponding disconnect devices or other apparatus specially provided for this purpose.

In practice, disconnect switches and circuit breakers are the most commonly used disconnect devices, and for simplicity, only these two types of devices are considered in this article.

A disconnect switch is a mechanical device that conducts electrical current and provides a point of efficient (usually visual) isolation of the substation equipment, that is, circuit breakers, transformers, etc. [7]. Its most significant functions are to open and close reliably when called upon to do so, to carry current continuously without overheating, and to remain in the closed position under faulty current conditions.

These switches are designed for nonload switching, opening, or closing circuits where negligible currents are made or interrupted. This means that if a disconnect switch is manoeuvred to interrupt or establish a significant current, an accident may be caused, with consequences for the safety of the service, installation and, above all, the people who perform the manoeuvre.

Figure 1 shows the electrical symbol used in the following layouts to represent the two possible states of a disconnect switch.

A circuit breaker is a switching device capable of making, carrying, and breaking circuits under normal circuit conditions and also of making, carrying, and breaking circuits for a specified time, and breaking circuits under specified abnormal conditions such as a short circuit [7,8]. For security reasons, circuit breakers must be able to be locked in order to inhibit opening and closing orders, thereby preventing untimely operation.

Figure 2 shows the electrical symbol used in this interface to represent the two possible states of a circuit breaker.

The main concept that students must learn is the difference between a disconnect switch and a circuit breaker in relation with the cutoff capacity. This implies that manoeuvres should be carried out in a logical order to protect people and facilities.

In this sense, the main conditions required for each manoeuvre are:

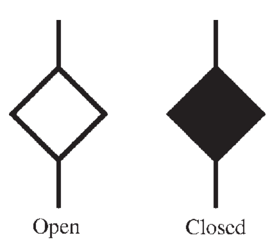

Figure 1 Electrical symbol of a disconnect switch.

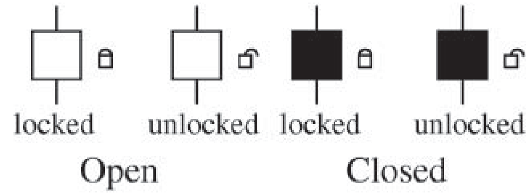

Figure 2 Electrical symbol of a circuit breaker.

- Never establish or interrupt a current by means of disconnect switch.
- In a closing operation, the disconnect switches must be closed first and then the circuit breakers can be closed.
- In an opening operation, the circuit breakers must be opened first and then the disconnect switches can be opened.
- Any accidental opening or closing the circuit breakers in the process must be prevented.

PLANNING AND DEVELOPMENT OF OPERATIONS IN ELECTRICAL SUBSTATIONS

When performing a manoeuvre, the first phase of work is to locate and identify the cutting equipment on which to act.

The manoeuvres will be analyzed on simplified one-line diagrams, and indicate only the order of operation of the disconnect devices. For this purpose it is necessary for students to consider the following factors: power quality and safety. Security plays an important role in conducting the exercise: first, by preserving the safety of people; second, installation security; and third, security of the service. It is important to clarify that, whenever possible, manoeuvres should be performed without affecting the service, although it must never compromise the safety of people or of the installation.

Therefore, students must be able to not only interpret a schematic one-line diagram of an electrical installation, but also conduct manoeuvres safely. In this regard, the educational tool proposed in this article has proved useful for students to learn in an active way as well as for their understanding of the philosophy of working safely.

At this point, one example is given in order to implement the theory explained in the preceding section. For example, Figure 3 shows the correct sequence for opening a line protected by two disconnect switches and one circuit breaker. First, the circuit breaker is opened, and once open, its locking mechanism is activated to prevent accidental closing and opening of the disconnect switches. However, to close a line, the order of operation would be: first block the circuit breaker in the open position to prevent accidental closure, then close the disconnect switches, then finally unlock and close the circuit breaker (Fig. 4).

DESCRIPTION OF PROPOSED SYSTEM

There are numerous configurations of high voltage substations that could be used in this article to show how manoeuvres can be taught [7]. However, the configuration shown in Figure 5 has

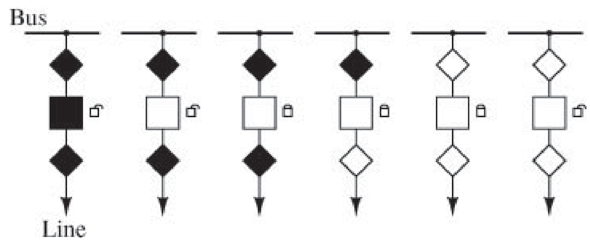

Figure 3 Correct order of operation during the line-opening manoeuvre.

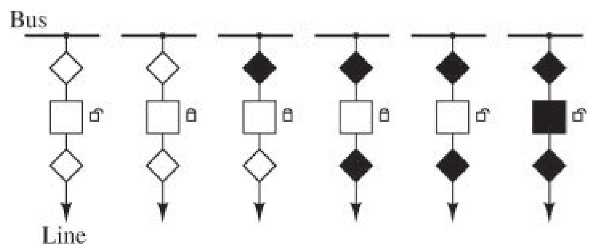

Figure 4 Correct order of operation during the line-closing manoeuvre.

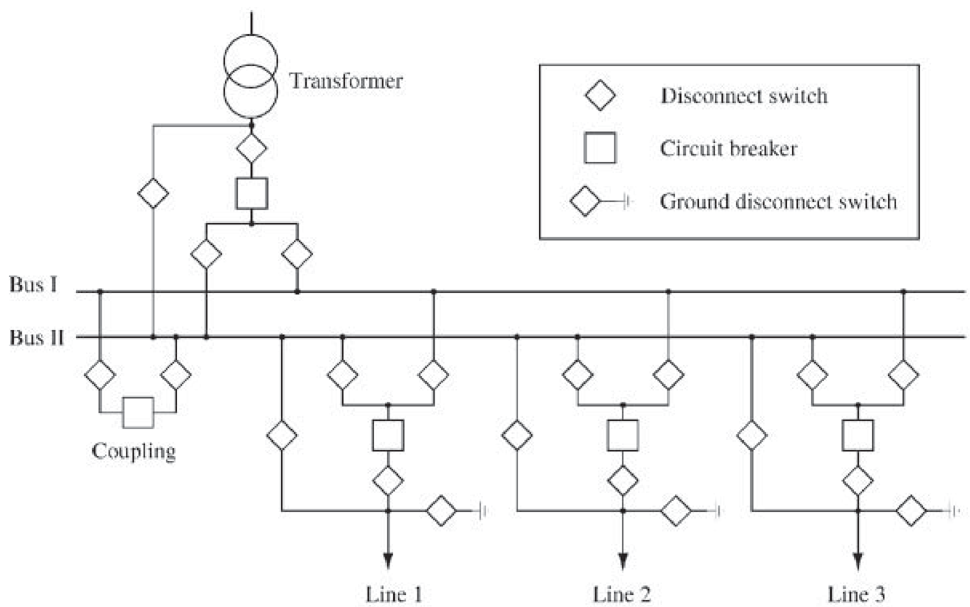

Figure 5 One-line electrical schema of the proposed system.

been chosen, which consists of a double-bus system with a by-pass, with one transformer position and three line positions. From an educational point of view, this configuration can replay virtually all the manoeuvres that may occur in reality, such as providing service to one or both buses, changing buses, serving a line, serving a line via the by-pass, and grounding a line, and yet it is sufficiently simple and intuitive enough to enable people to understand and to assume the philosophy of safe operation at all levels.

A case study of operations using the system of Figure 5 is given below. This constitutes the simplest case and each of the intermediate patterns is presented step by step as the manoeuvre progresses. Many more complex cases exist, as shown in Appendix, which are difficult to develop on the traditional blackboard and for which the interactive tool proposed in this article is very useful for visualization and development.

Example Case: Energizing Bus I

The initial situation is such that all disconnect devices are in the open position, with the entire system nonenergized except the transformer, which is in service, as shown in Figure 5.

The sequence of manoeuvres is as follows:

(1) Lock the transformer circuit breaker in the open position (Fig. 6). Given that Bus I is empty without voltage, a fault may occur which fails to be detected (i.e., fault isolation between phases or earth). If the circuit breaker is closed before the disconnect switches are closed, then a short-circuit current is established, with all the attendant consequences, both human and material.
(2) Close the two disconnect switches on the side of the transformer and Bus I (Fig. 7).
(3) Unlock (Fig. 8) and close the circuit breaker (Fig. 9).

DESCRIPTION OF THE EDUCATIONAL TOOL

This section describes the educational tool developed for the teaching, in the classroom, of the proper performance of manoeuvres in electrical substations. It consists of an initial window (Fig. 10) with a main menu that enables selection of the type of manoeuvre desired:

- Service a bus from the transformer.
- Couple the buses.
- Service a line.
- Change buses with service in the lines.
- Service a line via its by-pass.
- Out of service a line.
- Earth a line.
- Remove the by-pass of a line.
- Out of service a bus.
- Re-establish service to a line.

In turn, for each of the manoeuvres, additional configurations can be chosen depending on the initial state of the system elements. This greatly increases the number of solutions and thus the educational possibilities of the system. In total, it is possible to select 17 different configurations in the proposed tool. Hence, once the manoeuvre is selected, a second screen appears with a submenu. For example, Figure 11 shows the second screen when the manoeuvre number 3 is selected.

After selection of the desired configuration in the submenu window has been carried out, this then links to the screen shown in Figure 12. The central part of the screen shows the one-line diagram of the facility where the status of all the disconnect devices corresponds to the type and initial state of the selected manoeuvre. A menu is shown on the left side of the screen through which one can return to the main menu or submenu and can restart the manoeuvre or can go back to the previous step. The bottom of the screen displays an information panel where information is displayed regarding the type of manoeuvre being carried out, the current status of the operation, and details of any error.

The screen shown in Figure 12 constitutes the start of the manoeuvre, through which the student is allowed to intervene (Fig. 13).

From an educational point of view, the effectiveness of the determination of the concepts is closely related to the sensory impression brought to the student. Therefore, the design tool includes the broadcast of messages and images in order to reinforce this effect. For example, if a student makes a wrong manoeuvre, such as opening a disconnect switch before the circuit breaker, then communication is enhanced by a visual error indicator, such as that shown in Figure 14. In this case, the student may decide to find out the cause of the error by him/herself or

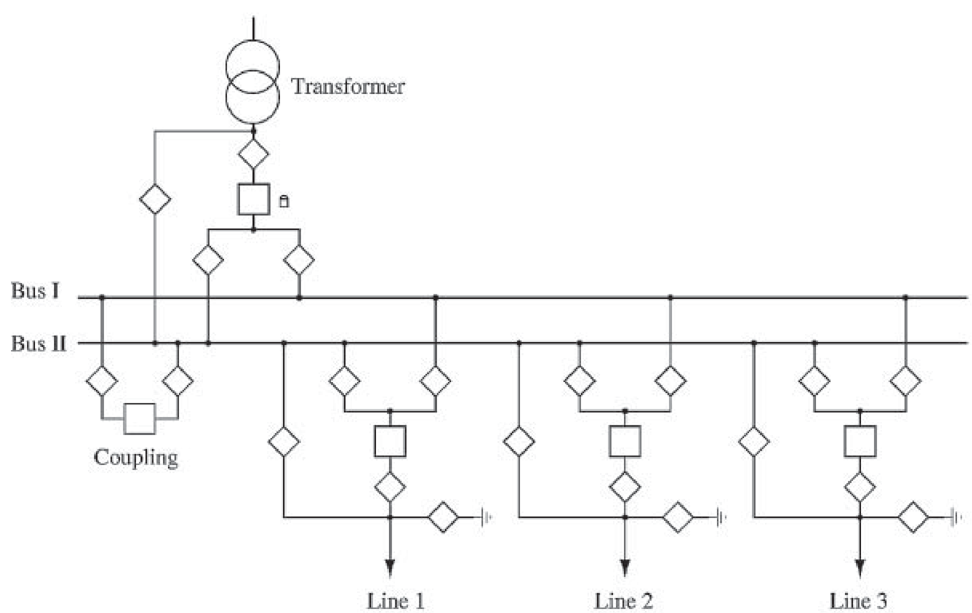

Figure 6 One-line electrical schema corresponding to the locking of the circuit breaker for Case 1.

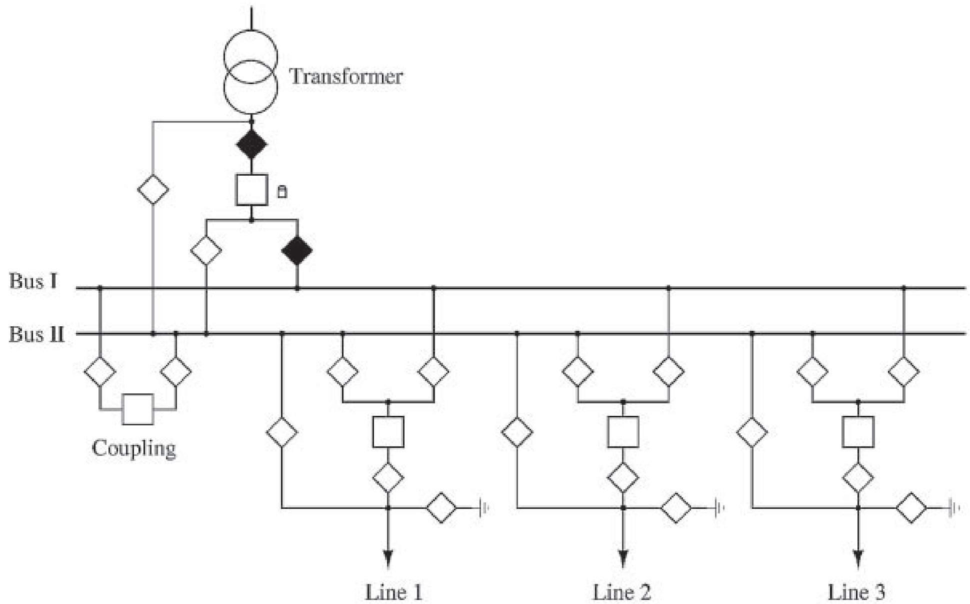

Figure 7 One-line electrical schema corresponding to the closing of the disconnect switches for Case 1.

to ask the program to display the error by pressing the ''error'' button.

If the ''error'' button is pressed, then the details of the error are presented in the information panel. For example, in the case of opening a disconnect switch before its associated circuit breaker the ''error'' message will be: ''A disconnect switch have been opened before its associated circuit breaker''. Once the error is identified, the student can choose to undo the last step and continue the move or start again from scratch.

If the operation is completed successfully a message appears in the ''status line'' of the information panel (Fig. 15).

CLASSROOM PRACTICE DEVELOPMENT

For many years, such practices have been carried out by drawing the one-line scheme on a blackboard. This methodology is viable when simple manoeuvres are involved; however in complex manoeuvres, this has many limitations. The development of the educational tool explained in this article together with the use of interactive white boards ensure optimal conditions for the transmission of knowledge.

The following will show how practice in the classroom is carried out. In small groups of 15–20 students, the manoeuvre

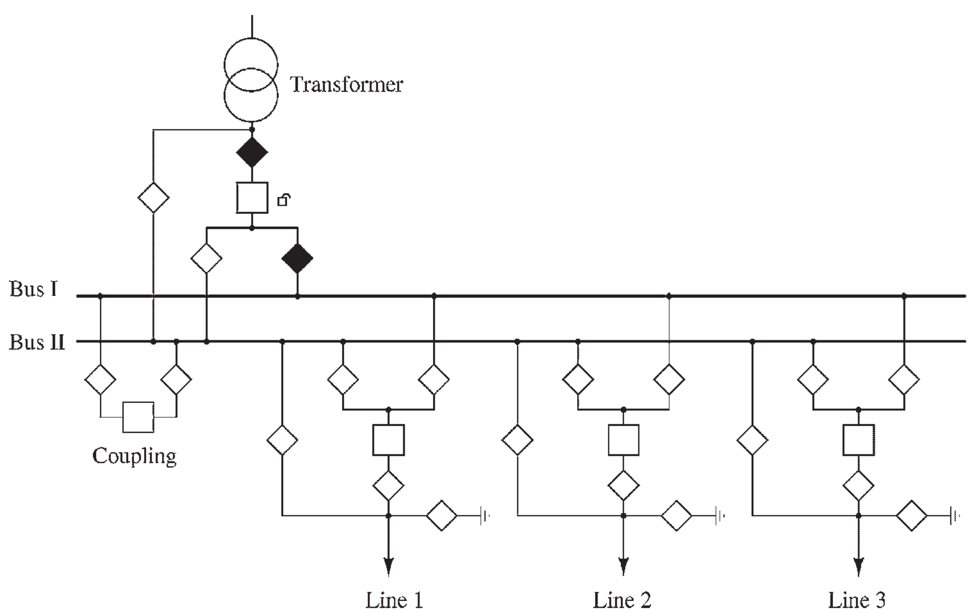

Figure 8 One-line electrical schema corresponding to the unlocking of the circuit breaker for Case 1.

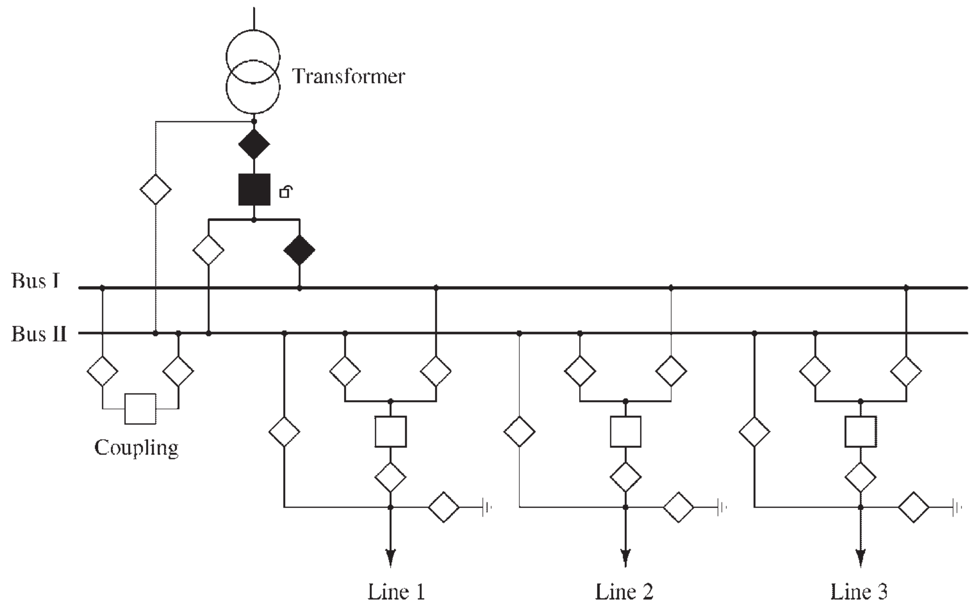

Figure 9 One-line electrical schema corresponding to the closing of the circuit breaker for Case 1.

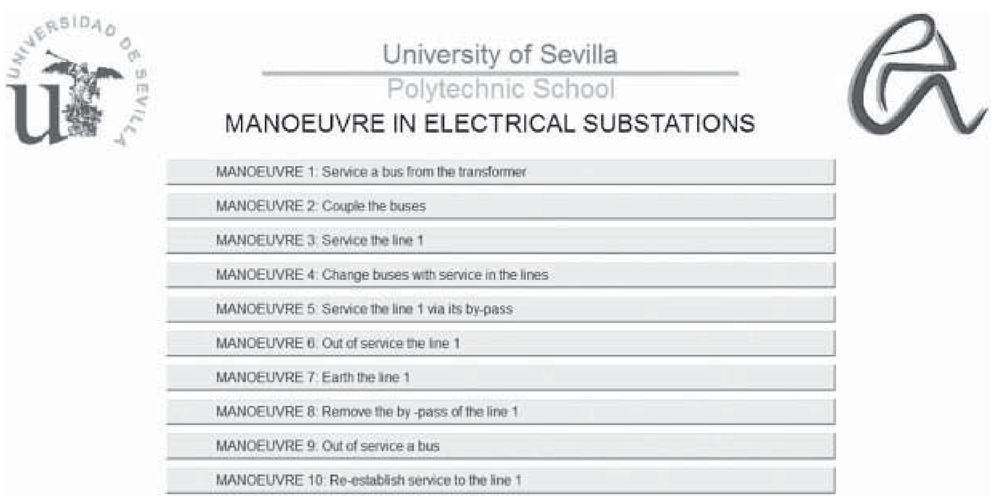

Figure 10 Initial window with the main menu selection of the manoeuvre.

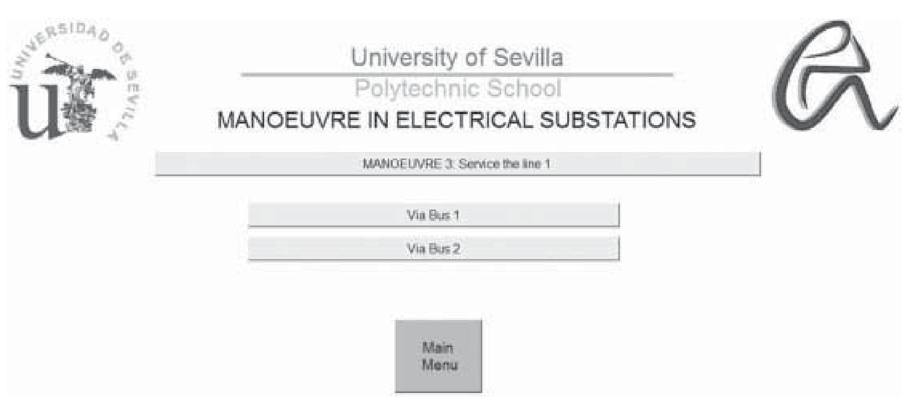

Figure 11 Second window with the submenu for the selection of the configuration for the selected manoeuvre.

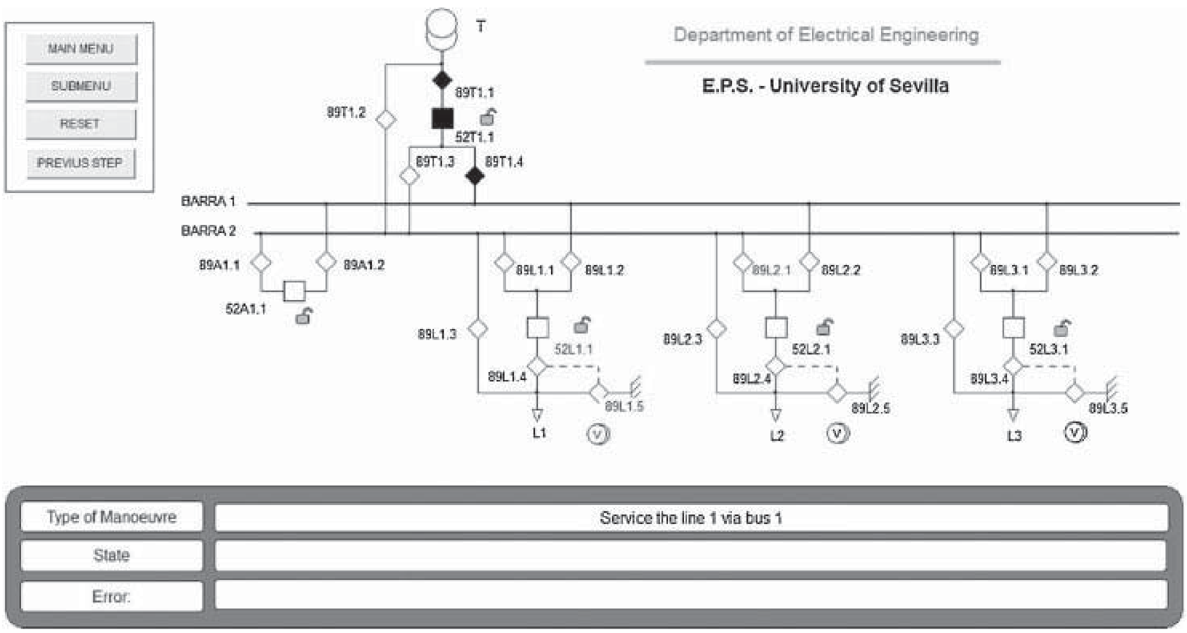

Figure 12 Screen used in the development of the manoeuvre.

to be realized is shown on the interactive white board, so that the students can familiarize themselves with the layout, symbology, and correspondence of each element with actual device installation.

Students are randomly selected to begin the sequence of steps to perform the manoeuvre. If students successfully complete the assigned manoeuvre, they are considered to have passed the test and to have completed their participation. However, if students make a mistake, they remain in the classroom waiting for a further opportunity to try again once all the others have had their turn, whereby another student is called upon to continue from the previous step, repeating the process indefinitely.

In this way, students are forced to follow the procedure closely and repeatedly, thus detecting and assimilating both their own mistakes and those committed by others during the practice. At any time, the teacher can take a break to explain or justify the more complicated steps, or the cause and consequence of errors that appear. Eventually, after a series of iterations, the number of students present naturally decreases, with those who have more difficulty understanding and performing being those who remain to redisplay the different manoeuvres being carried out. If some students continue to fail the test after a reasonable number of attempts, then they are called on to repeat the test at another time, thereby allowing the teacher to focus specifically on detecting and solving the learning difficulties of each student.

This procedure achieves a success rate of 100%, thereby fulfilling its objective. The authors believe that it is unacceptable for a student to obtain a degree in Electrical Engineering without at least understanding and successfully performing manoeuvres in high voltage as shown in this article.

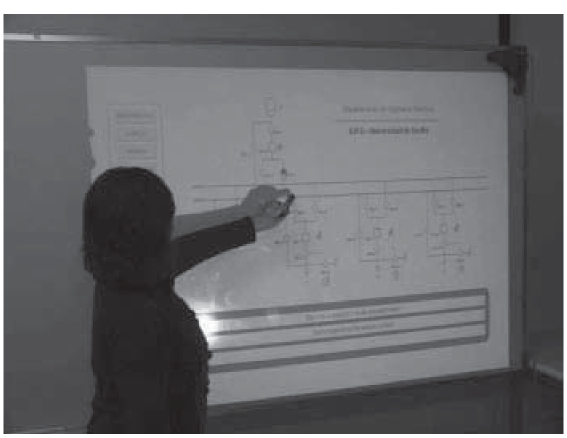

Figure 13 Student performing the manoeuvre.

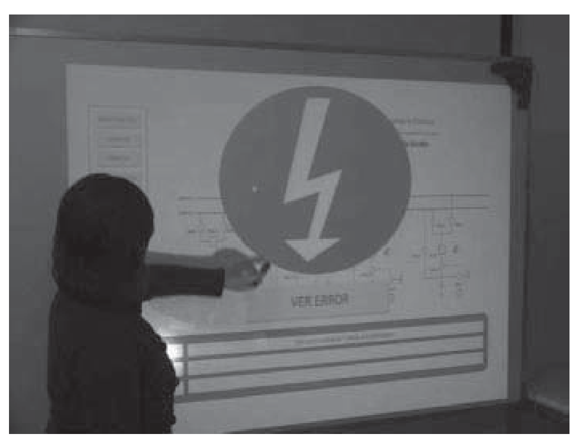

Figure 14 Error message indicating an incorrect manoeuvre.

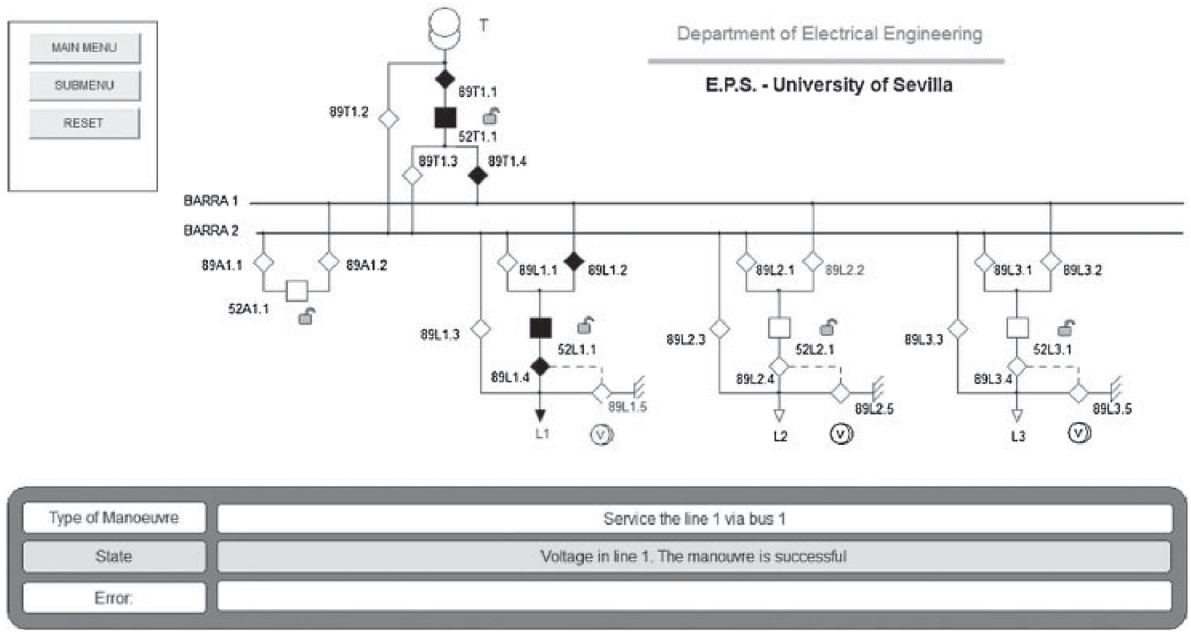

Figure 15 Screen indicating that the manoeuvre is successful.

EVALUATION RESULTS

At the end of the more recent semester, the university students were interviewed. An anonymous evaluation form was prepared for the assessment of the level of students' satisfaction, and of their opinions about the new educational tool. The questionnaire contains five questions based on a five-point Likert scale, coded as shown in Table I.

Figure 16 shows the results based on an attendance of 19 students out of 25 registered students (about 75%) to the High and Medium Voltage Electrical Installations course of the Electrical Engineering degree at the University of Seville, Spain.

It can be seen that all of the questions attained a positive assessment: 80% of answers were ‘‘Agree’’ and ‘‘Strongly Agree’’ and none of the responses was ‘‘Strongly Disagree’’ or ‘‘Disagree’’. From this result it can be inferred that students consider the proposed tool easy to use and useful for their education. In general, the perception of the improvement in learning and in the subject development has been positive, and over 95% of students clearly think that this practice should be repeated in the coming years.

A substantial consequence is that 90% of students think that this tool will be useful in their professional development, which constitutes the main incentive for the authors to use this tool in the classroom.

Finally, the answers given to Question 5 of the questionnaire clearly indicate that the tool developed here surpasses the traditional blackboard methodology.

CONCLUSIONS

The philosophy that work on electrical installations should be focused on safety is one of the pillars of the current operation of power systems. Therefore, knowledge on this topic must be incorporated into the curriculum of any student of Electrical Engineering.

Manoeuvres in electrical substations are fully involved through this philosophy. A good understanding by Electrical Engineering students on safe working methods, both for individuals and for facilities or service, allows these students to assimilate specific knowledge useful for their future working life and for a more general form of protection.

Table I Satisfaction Questionnaire

No.	Question	Answer				
		SD	D	I	A	SA
1	Is the interactive educational tool easy to use?					
2	After this practice, has your knowledge of electrical substation manoeuvres increased?					
3	Do you think this practice should continue being taught in the coming years?					
4	Do you think that this practice may be useful in your professional development?					
5	Do you think the use of interactive white boards has significant advantages over the traditional use of blackboards?					

SD, strongly disagree; D, disagree; I, indifferent; A, agree; SA, strongly agree

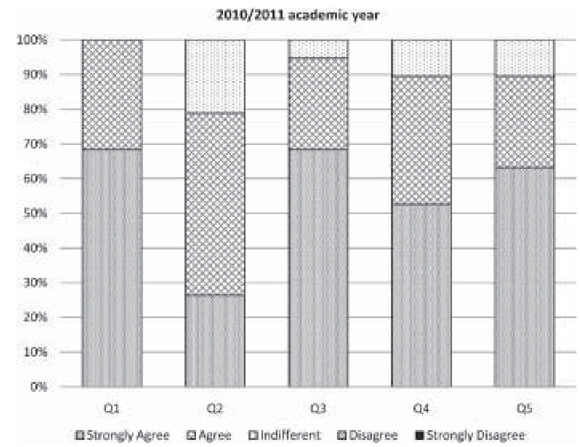

Figure 16 Results of the student questionnaire for the present academic year.

The educational tool presented here is specifically designed to achieve full knowledge of the working methods for manoeuvring in substations, based on an installation scheme that is simple and sufficient, and on a set of situations whose solution allows both the transmission of knowledge and the assessment of its assimilation.

The tool presented is currently used with great success in the process of training students of the Electrical Engineering degree taught at the Polytechnic School of the University of Seville.

ACKNOWLEDGMENTS

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APPENDIX: ENERGIZING LINE 1 VIA BY-PASS

The initial scenario is such that all lines and the transformer are connected to Bus II by their position and Bus I is without voltage (Fig. 17).

The aim is to feed lines 2 and 3 and the transformer for Bus I. If the line 1 is fed via by-pass, this is without the protection of the circuit breaker, and hence if there is a short circuit in this, it will be forwarded to Bus II and hence trigger all the circuit breakers attached to it. When replacing all connections to the Bus I, any faulty current must first pass through the circuit breaker of the bus coupling, which would cause this trip, which in turn would eliminate the fault and prevent the disconnection of other lines, thereby preventing loss of service to consumers.

The sequence of operations is as follows:

(1) Energizing Bus I:
   (a) The circuit breaker corresponding to coupling buses is locked in the open position. Since Bus I has no voltage, a fault may occur undetected (i.e., fault isolation between phases or earth). If the circuit breaker were closed before the disconnect switches were closed, then the opening of the disconnect switches would establish a short-circuit current with the resulting consequences, both human and material.
   (b) Close the disconnect switches corresponding to the coupling buses.
   (c) Unlock and close the circuit breaker.
(2) Change of Transformer Buses:
   (a) The circuit breaker corresponding to the coupling buses is locked in the closed position. In order to change the transformer connection of Bus I to Bus

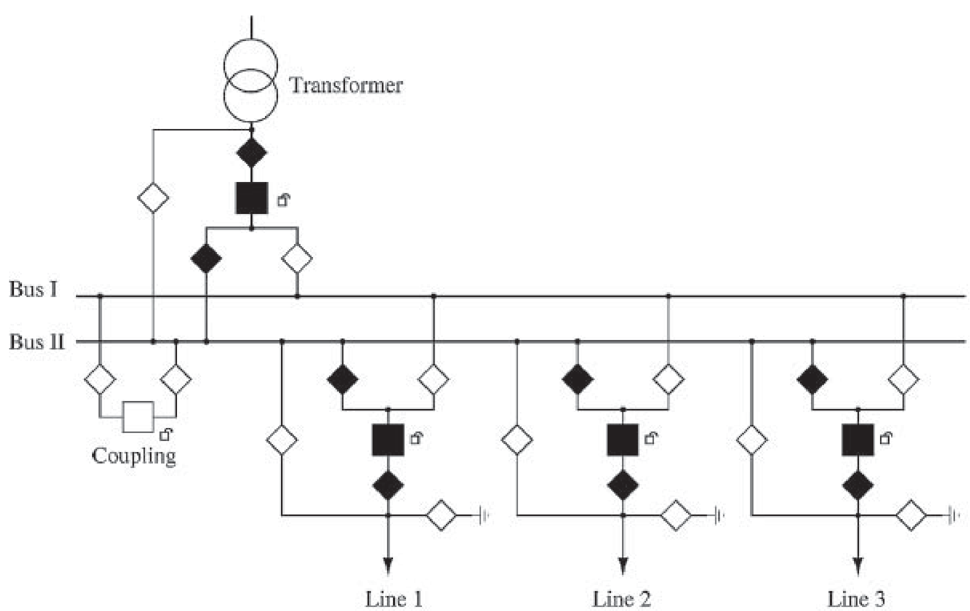

Figure 17 One-line electrical schema corresponding to initial state for Case 2.

II without interrupting the service, it is necessary to close the disconnect switch of Bus I and then open the corresponding disconnect switch to Bus II. Since the coupling allows an alternative path for the load, this manoeuvre can be carried out and implies no establishment or interruption of the current. However, if during the process there were a failure in Bus I, (such as a short circuit), and the circuit breaker corresponding to the coupling were opened, then the closure of the disconnect switch of Bus I would produce a short-circuit current, with all the inevitable consequences. Once the circuit breaker corresponding to the coupling buses were locked, any apparition of a short-circuit current would immediately open the circuit breaker corresponding to the transformer, thereby leaving the installation without voltage. Damage to persons or installations would be prevented due to the safety precautions followed, but to the cost of the continuity of the service.
   (b) Close the disconnect switch of Bus I.
   (c) Open the disconnect switch of Bus II.
   (d) Unlock the circuit breaker of the coupling buses.
(3) Change of Buses of Line 2:
   (a) Block the coupling circuit breaker in the closed position.
   (b) Close the disconnect switch of Bus I.
   (c) Open the disconnect switch of Bus II.
   (d) Unlock the coupling circuit breaker.
(4) Change of Buses of Line 3:
   (a) Block the coupling circuit breaker in the closed position.
   (b) Close the disconnect switch of Bus I.
   (c) Open the disconnect switch of Bus II.
   (d) Unlock the coupling circuit breaker.
(5) Energizing Line 1 by its by-pass:
   (a) Lock the circuit breaker of Line 1 in the closed position. In order to change the connection of Line 1 from the disconnect switch of Bus II to the disconnect switch of the by-pass without any interruption in the service, it is necessary to first close the by-pass disconnect switch in order to later open the disconnect switch of the connection to Bus II. Since the circuit breaker allows an alternative path for the load, this process can be carried out and implies no establishment or interruption of the current. However, if during the process there were a failure in Line I (such as a short circuit), and the circuit breaker corresponding to the line were opened, then the closure of the disconnect switch of the by-pass would produce a short-circuit current, with all the inevitable consequences. Once the circuit breaker of Line 1 were locked, any apparition of a short-circuit current would immediately open the circuit breaker corresponding to the coupling, thereby leaving Bus II without voltage. This would affect only Line 1 itself, since the rest of the service would be connected to Bus I. Damage to persons or installations would be prevented due to the safety precautions followed.
   (b) Close the disconnect switch of the by-pass of Line 1.
   (c) Unlock and open the circuit breaker of Line 1.
   (d) Open the disconnect switches of the line and of Bus II of Line 1.

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