Design and Implementation of a Reconfigurable Remote Laboratory, Using Oscilloscope/PLC Network for WWW Access

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***Abstract*—The objective of this paper is to present a remote laboratory in the context of power electronics education. New technologies and developments are compelling educators to deeply reflect on the traditional means of teaching. Modern curricula require new ways of conception and implementation of innovative pedagogical approaches. Often, these new pedagogical approaches require novel technological realizations. Although e-learning facilities are increasingly being used in engineering education, often, they are based on simulations and/or emulations of virtual laboratories. This paper presents a remote laboratory facility that allows the students to conduct real power electronics reconfigurable experiments through the Internet, promoting a more efficient learning through online industrial automation operation using the Internet and WWW services.**

***Index Terms*—Automation, education, power electronics, remote laboratory, supervisory control and data acquisition (SCADA) systems.**

I. Introduction

THE INCREASING progress in information technology has enabled the development of virtual/remote laboratories as pedagogical support [1]. Modern education concepts encourage the simultaneous use of onsite teaching with online activities, which is known as blended learning [2]. On the other hand, the process of convergence to a common educative space, within Europe, forces teaching institutions to adopt online courses.

Any engineering curricula should present a significant level of practical component. The developed practical skills should inspire the students to, among other issues, test learned theoretical concepts, interact with equipment, and analyze experimental data. Within engineering disciplines, laboratory experiments are essential to apply the studied theory and observe the differences between studied models and real equipment.

Working in real laboratories has become more and more expensive, involves supervision staff, requires scheduling, and presents time and space restrictions.

Virtual laboratories, providing simulation environment, have become an alternative to overcome the real laboratory disadvantages. They can be a good interactive medium, providing a good explanation of learned theoretical concepts. On the other hand, they present no time or place restrictions and can be maintained at a considerable low cost.

Although simulation-based virtual laboratories can accurately simulate real equipment (depending on the considered/developed models), the use of real laboratory experiments has an extra educational/pedagogical value, ensuring the reliability of the experiment.

Remote laboratories, where the students are able to interact and operate with real equipment, offer a higher level of training when compared with a simulation tool.

Although interacting with real equipment, remote laboratory facilities allow the overcoming of several teaching constraints related to teaching institutions' limited resources (human and material), for instance, the large number of students allocated to each experiment. With a remote experience, the students can, at any time, repeat the experiment and reevaluate their results.

Several models of virtual/remote laboratories have been reported in the literature [3]–[16]. These facilities present experiments in several engineering fields, such as power electronics, electrical machines, control engineering, instrumentation and measurement, or robotics. Casini *et al.* [3] present an automatic-control remote laboratory in which the students access several processes (dc motor, water tank, magnetic levitation system, helicopter simulator, and mobile robot) through the Internet. In [4], a Web programmable logic controller (PLC) remote laboratory is presented. Ko *et al.* [5] describe a remote virtual oscilloscope. Scutaru *et al.* [6] describe a knowledge management system in Virtual-Electro-Lab. Trevelyan [7] introduces several remote-laboratory experiences, from classical control systems to PLCs. Fernandes *et al.* [8] present a real power electronics converter experiment, which the students can access through the Internet. In [9], a remote LabView-based platform is described for several circuits, sensors, and actuators. In [10], the study of a stepping motor is established in a mechatronic context. It presents a Web-based courseware where the image and sound of the experiment is transmitted in real time. Leleve *et al.* [11] describe a remote laboratory applied to a vertical store. In [12], the students have to develop a control program using a normal Internet browser. Bogosyan *et al.* [13] present a remotely accessible electrical drive set for education in electrical machinery. A Moodle-based booking system for a remote laboratory is described in [14]. Garcia *et al.* [15] present a distributed network control system with a flexible control procedure and TCP/IP connection. Walter-Colombo *et al.* [16]

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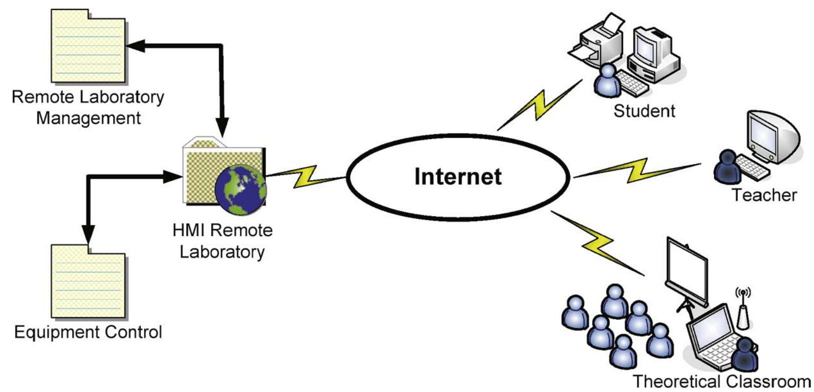

Fig. 1. Remote laboratory functional components.

present the design of an agent-based control system for industrial manufacturing with TCP/IP communication.

This paper presents a remote laboratory facility implemented at the Electrical Engineering Department of Setubal's College of Technology (Escola Superior de Tecnologia de Setúbal), Portugal. A novel solution was developed, where PLCs and oscilloscopes are fully integrated into the same industrial network combined with a supervisory control and data acquisition (SCADA) supervision system. The described system is highly reconfigurable, supporting several working benches with different experiments. This paper is a consequence of other successful pedagogical proposals, such as an oscilloscope network [17] and an industrial automation process simulator [18]. The developed remote laboratory deals with power electronics converter experiments, but because it relays on a PLC/Ethernet-based solution, it can easily be extended to other engineering fields. The rapid and easy creation of different interactive remote control experiments is a consequence of a combination of hardware and software solutions [28]. The Internet integration of field bus systems enables information from supported devices to be exchanged across equipment and users, which can also be remote users [19].

II. Functional Overview

The developed system is based on a standard client–server application. This topology simplifies the architecture on the server side and expands the system capabilities. Fig. 1 shows the main functional components of the remote laboratory.

The remote laboratory is accessed, via Internet, through a human–machine interface (HMI). This HMI requires a password authentication and gives access to the physical system itself. The main functional components are the remote laboratory management and the experiment control. The functional disjointing of these two features allows the uncoupling of the software management (which resides in the remote laboratory server) from the physical access to the experimental equipment (which is made through a PLC/Oscilloscope Ethernet network), as it will further be explained in the Section III.

The Internet access can be made by the students (to perform the desired experiment), by the teacher (to modify the experiment parameters), or by the teacher in a classroom environment to complement its theoretical explanation.

The remote laboratory management includes features such as user login and logout, user and password management, e-mail services, user access records, and time-out management.

The experiment control includes features such as access to the physical experiment equipment, measurement system, and control and security of the selected experiments.

III. Architecture Overview

One of the goals when developing the remote laboratory architecture was to set up a local area network (LAN) that connects each working bench of the remote laboratory to a local server. Fig. 2 shows a general overview of the developed system's architecture. The LAN connects the local sever, the several PLCs, and the oscilloscopes. This LAN has an Ethernet IP layer industrial protocol supported over TCP/IP protocols.

A wide area network (WAN) is considered, through the Internet, to establish connections between the laboratory and the students and/or teachers.

In each laboratory working bench, three basic hardware components are considered: the experiment physical modules, a PLC that governs, selects, and controls the experiment, and one or more oscilloscopes that acquire the desired signals.

It is important to note that, first, several working benches can be considered, and second, more than one experiment can be set up in each bench. These several experiments are then governed by the PLC. Fig. 3 shows an example, where a single-phase controlled ac/dc converter is combined with a single-phase ac/ac converter, altogether in the same working bench with one PLC. These standard circuits are essential for the students to understand recent developments in power electronics. Fundamental research on power ac/dc converters has been reported in the literature [20]–[22]. New control strategies for power ac/ac converters have also been recently reported [23].

In Fig. 3, DO and AO denote the PLC's digital and analog outputs, respectively. R1, R2, and R3 are the relays used to choose the desired load. Relays Ra and Rb are used to select the desired experiment.

The control of both experiments is made by the PLC according to the user's selection. After logging in into the HMI remote laboratory, the student decides which experiment to perform. By selecting the ac/dc experiment, the PLC switches on the

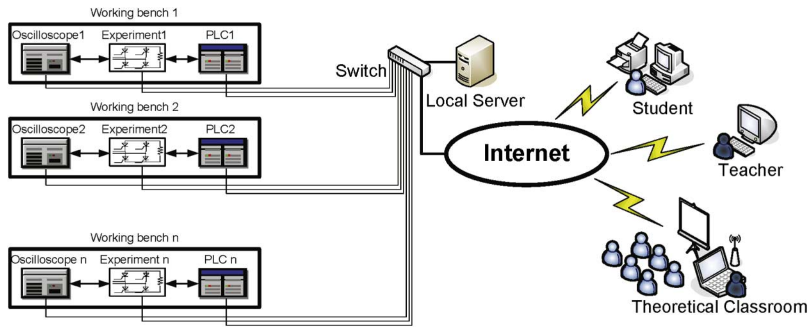

Fig. 2. Remote laboratory architecture.

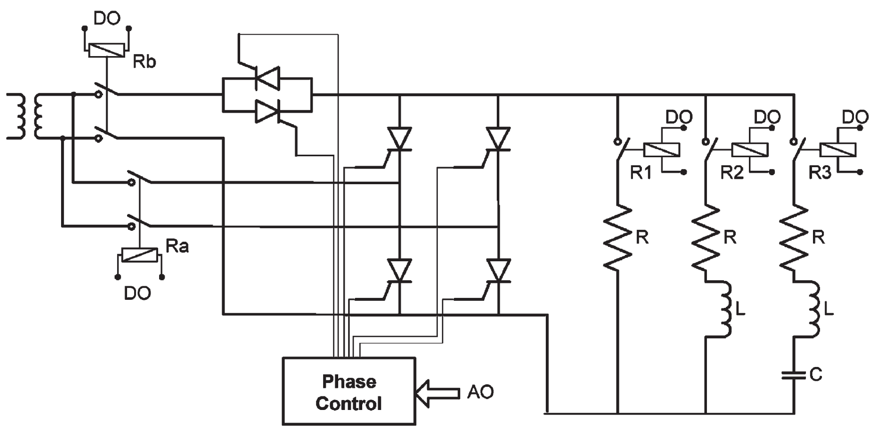

Fig. 3. Experiments conducted in the remote laboratory.

relay Ra. On the other hand, if he chooses to perform the ac/ac experiment, relay Rb is switched on. The student can also select the power converter load (R, RL, or RLC series). According to the student's choice, the PLC switches on one of the R1, R2, or R3 relays.

An error on the control-command design can involve safety problems and breakdowns on the experiment, the safety of people and the equipment being an essential aspect that is to be guaranteed [27]. Security interlocks are implemented in the PLC to avoid equipment damage. For instance, one cannot have simultaneous switching of Ra and Rb or R1, R2, and R3. Other than that, R1, R2, or R3 can only be switched on after power has been established through Ra or Rb.

Fig. 4 shows one of the working benches, with the PLC (1), the Ethernet switch (2), the oscilloscopes (3), the power converter (4), the R load (5), the load relays (6), the phase angle control unit (7), and the power supply (8).

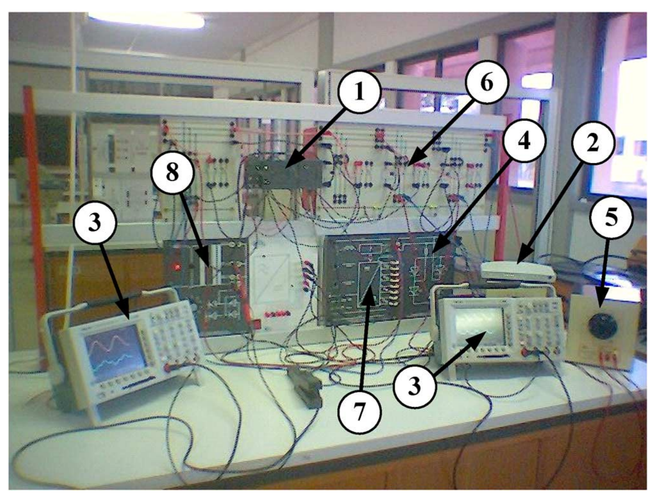

Fig. 4. Remote laboratory working bench.

IV. Main Hardware Components

The main goal of the developed system consists of allowing the students to perform a remote power electronics experiment over the Internet. Each student is able to choose the desired experiment, the converter load, and the phase angle. The system provides the control of the physical converter and the acquisition of the several voltage and current waveforms.

The used power converter and respective control unit are standard didactic equipment (from Lucas Nulle) for general use in laboratory classes. The control unit has an external input (0–10 Vdc) that allows the choice of the phase angle.

The experiment is ruled by a SIEMENS PLC (S7-200 with 224XP CPU). This PLC has 14 digital inputs, 10 digital outputs, 2 analog inputs, and 1 analog output. Its program assures the experiment and load management, the security interlocks, and signal conversion for the phase angle. This PLC is equipped with an Ethernet communication expansion unit (SIEMENS CP 243-1 IT) enabling the connection, via the LAN network, to the SCADA system implemented in the local server. It enables two communication speeds (10 and 100 Mb/s) and allows one FTP server connection, one FTP client connection, one e-mail client connection, and four HTTP connections. The PLC is accessible through the Internet either to be programmed or to allow the exchanging of information (writing and reading) between the user and the experiment.

The oscilloscopes used are Tektronics TDS3014B equipped with an Ethernet communication port. The SCADA system receives the oscilloscope acquired signals (either as a figure—BMP or EPS—or as a data stream—ASCII) and manages the oscilloscope parameters. This is a particular interesting feature because the student can obtain the voltage/current signals as he pleases the most, either as a figure or a stream of data to be processed. The entire set of oscilloscope measurements (root mean square, average value, and frequency) are available in the SCADA system, and all of the oscilloscope parameters (V/div, Time/div, channel on, and channel off) can also be set up by the students.

The switch is a standard eight-port switch from 3COM, and the local server a standard personal computer.

A typical question can be posed: How to prove to students that they are not acquiring signals from some simulation system? A simple Web camera allows the student to "see" the results of its choice. This camera is connected to the local server and enables live broadcasting through the SCADA system.

V. Reconfigurable System Integration

The architecture described in the previous sections allows a wide range of scenarios. The SCADA system allows access to perform the desired experiment or to modify the experiment parameters (facility that is only available for the teachers). One of the significant challenges for current and future manufacturing systems is that of providing rapid reconfigurability in order to evolve and adapt to the user requirements [24]. Also, the interoperability of field bus systems with external systems and applications should be considered [25].

Through the Internet, the teacher can easily change the experiment's parameters from any place. On the other hand, the SCADA system allows the control of the experiment and the remote parameterization of the oscilloscopes.

SCADA systems were first used in the 1960s and have been used to monitor and control plants or equipment in industries such as telecommunications, water and waste control, energy, oil, and gas refining, and transportation. These systems have rapidly evolved and are now supervising industrial systems with a large number of inputs/outputs. On the other hand, their interfacing capabilities have also expanded, providing open database connectivity and ASCII import/export facilities to communicate with distinct equipment. Typical SCADA functionalities comprise HMI, trending, alarm handling, logging and archiving, and report generation and automation.

Within the developed remote laboratory, the LAN network is connected to a local server where a SCADA system is running. Because the implemented SCADA system is Web-enabled, the local server acts simultaneously as a SCADA and an Internet server. The SCADA system was developed over the SIEMENS WinCC Flexible 2005 platform. To program the PLCs, the SIEMENS Step7 Microwin (V 4.0) was considered. To integrate the oscilloscopes into the developed SCADA system, the Tektronics e*Scope Web-based Remote Control software protocol was used.

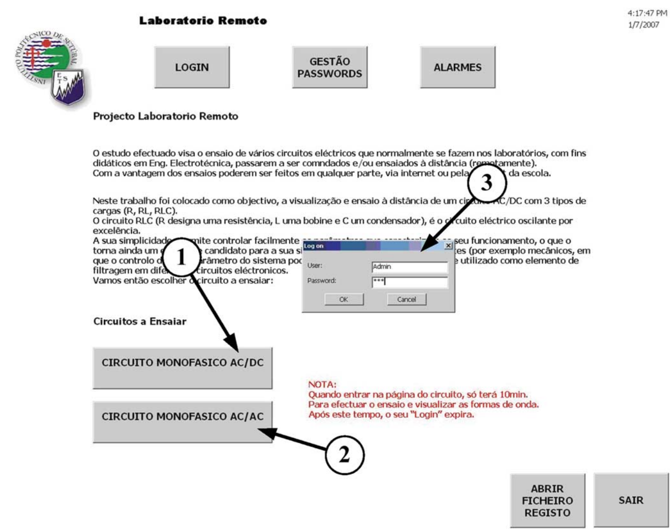

Fig. 5. Remote laboratory main screen.

The SCADA system runs over the Windows 2000/XP Professional Edition and allows 500 different screens with a maximum of 400 fields per screen and 2048 communication tags for data exchange within the supported LAN. The several screens were built with the use of an embedded graphic programming tool. More complex features, such as user's access records, were implemented with visual basic scripts. The user's historical access information is stored in a text file and is accessible to the teachers. The developed screens are stored, in the server, as standard HTML pages, thus providing the remote access via a regular Web browser. The local server has a static IP address for remote Web access. The IP addresses of the other LAN components (oscilloscopes and PLCs) are assigned in the server. Using the Tektronics e*Scope Web-based Remote Control software protocol, a visual basic script was developed in order to communicate with oscilloscopes assigning the proper commands. Step7 Microwin allows the PLC's programming, over the LAN, using two of the languages defined in the IEC61131-3 standard [26]: Instruction List and Ladder Diagram.

VI. Operation

After accessing the remote laboratory, via the Internet, the student is asked to register itself (remark (3) in Fig. 5). Only authorized users have access to the system. After logging in, the student can select one of the two available experiments: single-phase controlled ac/dc converter (1) or single-phase ac/ac converter (2).

After choosing the experiment, the student must specify the load. Fig. 6 shows the available options: R load (1), RL load (2), and RLC load (3).

In Fig. 6, it is important to note remark (4). It displays the remaining time that is available for the student to perform the experiment, which is available in every experiment's screen. For security and operationability reasons, a time-out was implemented. After this time has expired, the system automatically logs the student off.

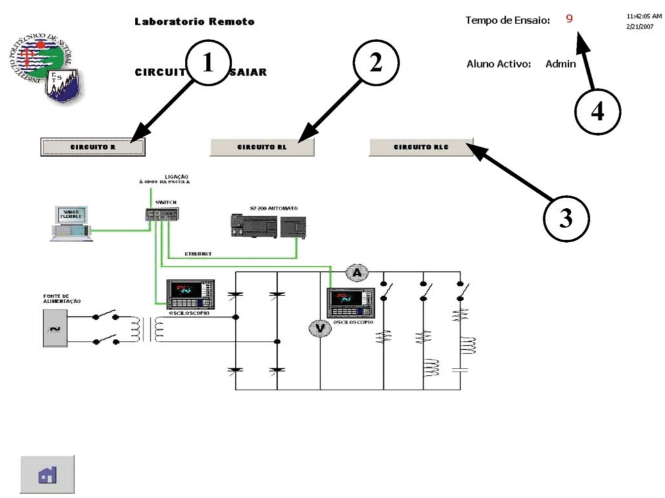

Fig. 6. Remote laboratory (single-phase controlled ac/dc converter) choice of load screen.

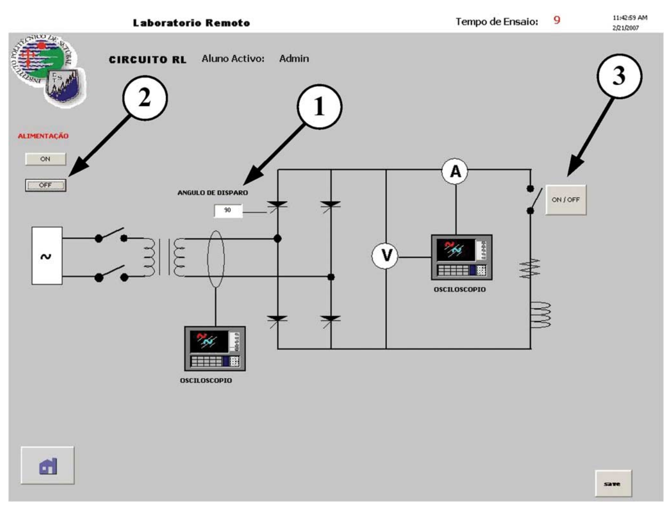

Fig. 7. Remote laboratory single-phase controlled ac/dc converter screen.

The system also allows the administrator (teacher) to state a limited number of accesses to each registered user (student). In this way, one single student cannot monopolize the system.

After choosing the load, the student is able to begin the experiment itself. The student can modify the phase angle, which is denoted by remark (1) in Fig. 7. The PLC only accepts valuable phase angles (between 0° and 180°). Any value outside this range generates an error message for the student. It is important to note that the phase angle can be changed anytime during the experiment without switching off the load or the power supply.

To start the experiment, the student must switch on the power supply—remark (2)—and then the load—remark (3). The PLC has a security interlock implemented, forbidding the load to be turned on before the switching on of the power supply.

The PLC also monitors the state of the circuit, reporting alarms on any unusual behavior. For example, an alarm is generated if the PLC switches on a relay and does not get back the respective on status information.

While performing the experiment, the student can select which oscilloscope to monitor and/or acquire signals. After selecting the power supply oscilloscope, Fig. 8 will be displayed.

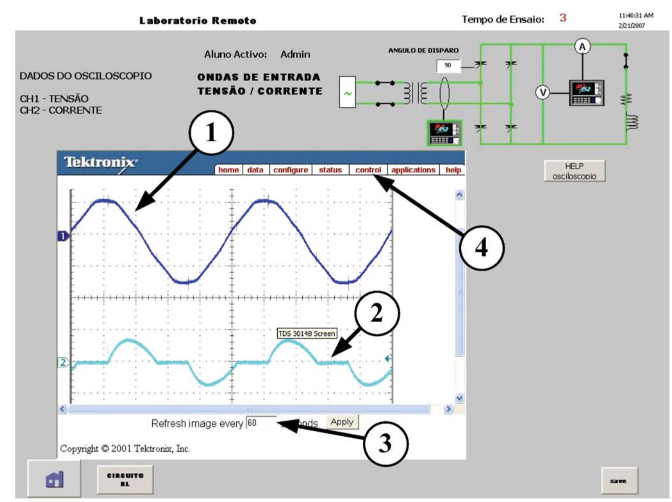

Fig. 8. Remote laboratory (single-phase controlled ac/dc converter) power-supply oscilloscope screen.

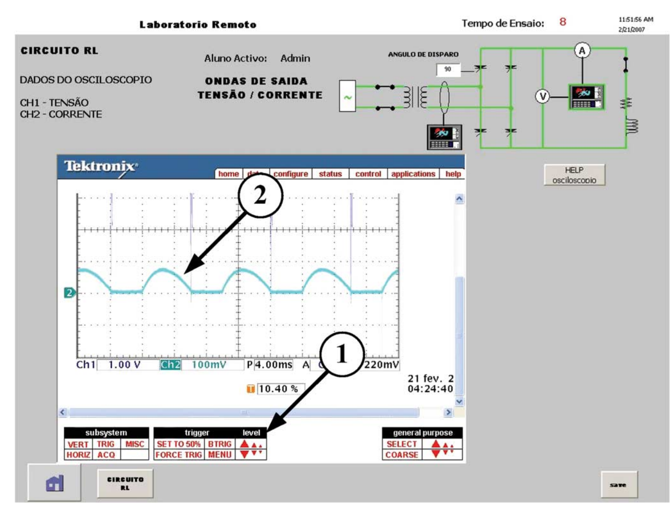

Fig. 9. Remote laboratory oscilloscope control screen.

Fig. 8 shows the supply voltage signal—remark (1)—and supply current signal—remark (2)—for an RL load. The displayed signals are exactly what the oscilloscope is acquiring. The image refresh time—remark (3)—and the phase angle can be changed during the experiment.

If the student desires to change any of the oscilloscope parameters, he should pick the control icon, which is denoted by remark (4) in Fig. 8, and the oscilloscope control screen will be presented (Fig. 9).

Fig. 9 shows some of the available oscilloscope control parameters (VERT, HORIZON, TRIG, and ACQ)—remark (1)—and the load current acquired by the load oscilloscope—remark (2).

The SCADA system also allows the student to send, by e-mail, the acquired image to a colleague or to his teacher. This is a particular interesting feature that allows result sharing without accessing the student's own e-mail account. Fig. 10 shows this procedure.

Allowing the students to have a very close behavior of the real experiments, the developed remote laboratory presents several important features: transparency (the user does not

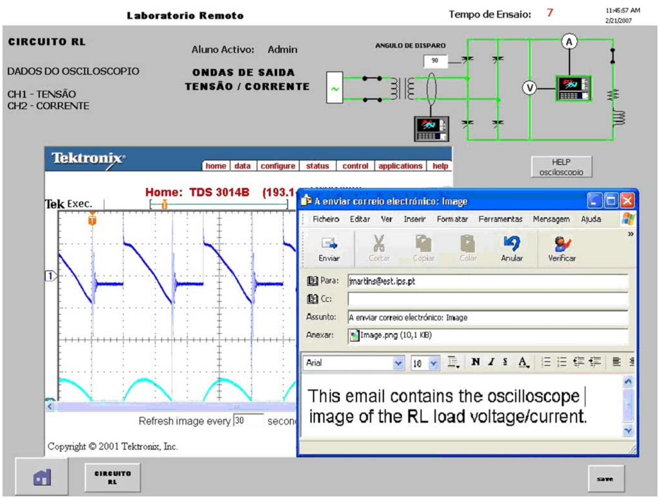

Fig. 10. Remote laboratory e-mail screen.

need any special training), accessibility (the laboratory can be accessed, via the Internet, with a regular Web browser), acquisition (the waveforms can be acquired as BMP or ASCII files), and measurement (fundamental measurements of the circuit can be obtained from the oscilloscope). From the point of view of the teacher, fundamental features are also considered: remote configuration (the remote laboratory can be distance-reconfigured), student's management (the student's access can be changed, and an access history is recorded), configurability and modularity (the power electronics experiments can be easily configured because they relay on basic modules), and flexibility (working benches can be added or removed from the LAN).

VII. Security

The developed security strategy considers a two-level hierarchical security model integrating a lower security level in the PLCs and an upper security level preformed by the SCADA system. Some of the considered security measures were already described in the previous section; however, they will be listed accordingly to their respective level.

The lower security level considers the following PLC security interlocks that avoid equipment damage:

1) source and load relay security interlock (the switching on of the load is allowed only after the switching on of the power supply);
2) phase angle limitation (the phase angle range is limited to 0°–180°);
3) time-out experiment shutdown (if a student exceeds the allowed experiment time, the PLC automatically shuts down the experiment, disconnecting all relays).

The upper security level considers the following local server access security measures:

1) access management (two user levels were considered: teacher and student, where only the student has access to the experiment itself);
2) password access (the system is only accessed via an authorized password);
3) password management (the teacher can create new users—students—and/or remove older ones);
4) alarm handling (the teacher has access to the list of generated alarms);
5) logging (the teacher has access to the historical access of all students, with respective session dates and times);
6) time-out (the system considers a time-out; after which, the student is automatically logged off);
7) frequency and access management (the teacher can configure the number and frequency of the access allowed for the students).

The remaining experiment time is constantly shown in the upper corner of the HMI interface.

Regarding frequency and access management, the teacher can configure a maximum number of access to each student, for each experiment, and a minimum time between access.

VIII. Preliminary Result Evaluation

The present system was implemented last year (2007), covering two teaching semesters within the basic power electronics course. This course is mainly composed of four modules (ac/dc, ac/ac, dc/dc, and dc/ac converters) that are fully complemented with laboratory experiments. From a total group of 48 students, the remote platform was used by 16 volunteer students (which means four working groups). All of the 48 students performed the experiments in the laboratory, but the 16 volunteers could also access them through the remote laboratory. The volunteer group used the platform for a four-month period, and at the end, each student presented a report containing the analyses of the experiments and their opinion about the remote laboratory. The obtained results are very preliminary on account of the short trial period and the number of students involved. However, based on the students' reports and on the teacher's view of the classes, some remarks can be made:

1) The students feel that the onsite laboratory contact is still very important;
2) The volunteer group presented better reports, including results that were not initially required;
3) Students without remote access prepared their experiments better (they knew that the experiment was not accessible again);
4) The volunteer group asked fewer questions to the assistant teachers (they knew that the experiment was to remain accessible for them).

One of the strong points of the remote laboratory is the ability to lead the students, incrementing their autonomous work abilities, self-discipline, and responsibility. On the other hand, it could diminish their group working spirit or their leadership skills.

A more accurate investigation on student satisfaction will be performed in the future, expanding the number of students with access to the remote laboratory. The students will also be allowed to present and discuss online their reports through the Moodle platform.

IX. Discussion and Remarks

New trends in teaching and learning strategies, in which blended learning is one of the most promising, can benefit from remote laboratories as valuable pedagogical add-ons. Experiments conducted in a real laboratory are undoubtedly the essential learning experience. However, remote laboratory facilities allow the students to access the laboratory infrastructure at nonworking hours. From the point of view of the teaching institution that offered services, this pleases the students very much.

This paper presented a remote laboratory that can be seen as a contribution to integrate those methodologies into regular electrical engineering curricula. The teachers and the students have presented a favorable opinion about the developed system. In spite of the ongoing evaluation period, the platform will be enlarged to the field of electric machines.

The developed remote laboratory considers a two-level SCADA system, with a LAN that interconnects all equipment (local server, working-bench control PLCs, and oscilloscopes). The access is made through the Internet via an HMI interface established in the server. The students can choose between different experiments and change several parameters, such as type of load or phase angle. The teachers are able to manage the system and even distance reprogram the PLC's software.

Several security measures and interlocks were implemented in order to avoid equipment damage and keep the usage of the system clear.

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