A Computer-Based Testing System to Evaluate Protective Relays as a Tool in Power System Protection Education

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ABSTRACT: Teaching power system relaying is a fundamental issue in a power system high-level course. However, for an effective instruction of this topic an experience with real equipments can be considered as fundamental. To achieve this purpose, in this paper a new approach for the practical learning of power system relaying is presented. This consists of a computer-based testing system of relay-operating characteristic. Different relay types and developed specific software are also an important piece of the laboratory practice. Using this system it is possible to understand the performance and limitations of different protective relay systems and to test a real relay disoperation. The benefit of using this system is not available through traditional lectures and textbooks. © 2009 Wiley Periodicals, Inc. Comput Appl Eng Educ 20: 19–28, 2012; View this article online at wileyonlinelibrary.com/journal/cae; DOI 10.1002/cae.20369

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INTRODUCTION

Service quality in power system network is one of the most important issues at present. Related with that, one of the essential components in power networks is the protective relaying. Its purpose is to safeguard the expensive equipment and maintain system integrity, which is necessary for continuous and economical supply of electric power to customers. Therefore, teaching the composition and behavior of protective relays is very important in a power system high-level course.

Over the years, the cost and difficulties to give a field experience to the students were mainly limited by the teaching of protective relaying. Meanwhile, efforts to improve this subject have been made; for example, using new technologies such as video films, PowerPoint presentations, and others.

Another approach to teach power systems and protective relays is the use of several tools based on personal computers [1–9], since nowadays they are widely connected to a network, in which several web-based tools appear [10–13].

However, the evaluation of the actual performance and possible dysfunction of a relay in the field through computer simulation is very difficult [14–18]. Therefore, physical laboratory is an important facility in the education process of the protective relay systems.

To overcome this problem, other approaches were used. A Power System Simulation Laboratory based on a scaled-down physical power system is one of the examples [19–21].

Other example is a virtual laboratory that uses real equipment distributed among multiple universities from which remotely located students can perform experiments. However, although these are important advances in order to bring some real experiments to the students, they cannot program a real relay and evaluate it.

To give to the students a real protective relay environment, in Setúbal Superior School of Technology (Politecnic Institute of Setubal), a laboratory equipped with industrial relays in conjunction with a computer-based testing system of the relay-operating

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characteristic was implemented, which was meanwhile developed. The digital relay types were an offer from commercial power system companies. The other relay types (electromechanical, solid-state) were an offer from electrical distribution companies.

The testing system of the relay-operating characteristic was developed in this school. Therefore, the implementation costs of the laboratory were very low. This paper is organized into seven sections. The first section gives the introduction. In the second section, the motivation of the proposed approach for teaching power system protection is presented. Some details of the relay testing system are presented in the third section. Relay types that can be used are discussed in the fourth section. Details about the developed prototype are presented in the fifth section. In the sixth section, some experimental laboratories tasks that can be made and some case studies with the corresponding results are shown. Finally, in the seventh section the conclusions of the work are synthesized.

MOTIVATION

For many years we use classical methods to teach power system relaying. We also use simulation tools to teach our students. However, we verify that the instruction is not effective. On the other hand, student's motivation is not very high. In this manner, we change our teaching approach, introducing the following goals:

- Proposing final year projects (each group has two students) to develop a real relay testing system. With this kind of project students must use a lot of knowledge from other areas, such as power systems relaying, power electronics, and programming. At the end they will be very proud because they feel that they created a real prototype.
- To program real relays and use a testing system to verify the protection settings that they introduced. This is also used to create a competition environment. Some students introduce the protection settings and other students use the testing system to verify the work of their colleagues. This increases the student's motivation to the top.

RELAY TESTING SYSTEM

The testing system of the relay-operating characteristic consists in the computer equipment with a simulator that provides several choices for the different fault type, a controller I/O interface and power amplifiers. The testing system main architecture is represented in Figure 1.

According to the fault type, the test signals are generated and converted in current and voltage references for the power amplifiers controllers. This is done using a microcontroller to connect the digital simulator to the power amplifiers, which are based on 2 three-phase inverters with a neutral wire.

The simulator inside the computer equipment was developed in Matlab/Simulink which allowed the testing and also the evaluation of the relay-operating characteristic. Matlab/Simulink has become one of the most widely used computer programs for the simulation of almost all kinds of dynamic systems [22–26].

The simulator communicates with a microcontroller in a bi-directional way. This allows sending the information for the

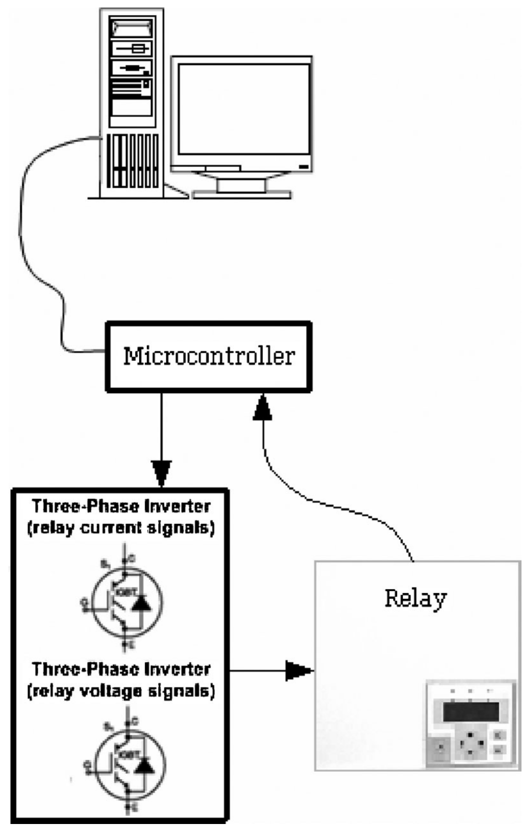

Figure 1 System main architecture.

power amplifiers and, at the same time, to receive information from the protection relay.

This relay testing is flexible in configuration and parameter adjustment and provides a rapid execution of new and different test cases. This system also allows testing different relays from different manufacturers because the software was designed with this feature and the power amplifiers were dimensioned for analog relays also.

The digital simulator allows testing different fault types, such as:

- Over load line current.
- Three-phase short circuit.
- Phase-to-phase fault.
- Phase-to-phase-earth fault.
- Phase-to-earth fault.
- Underfrequency and overfrequency.
- Undervoltage and overvoltage.

Figure 2 shows a Matlab/Simulink screen where a simulation is running. The different components of the simulator and the connection with a real relay can be seen. In this way, students can see how all parts of the relay testing system work. They can also compare the obtained simulation results with the experimental results.

Students can also define in the Simulink the amplitudes and angles of the voltage and currents that the real power amplifier will apply to the relay. Another advantage of the developed program is that it allows the students to make a Matlab/Simulink simulation of a

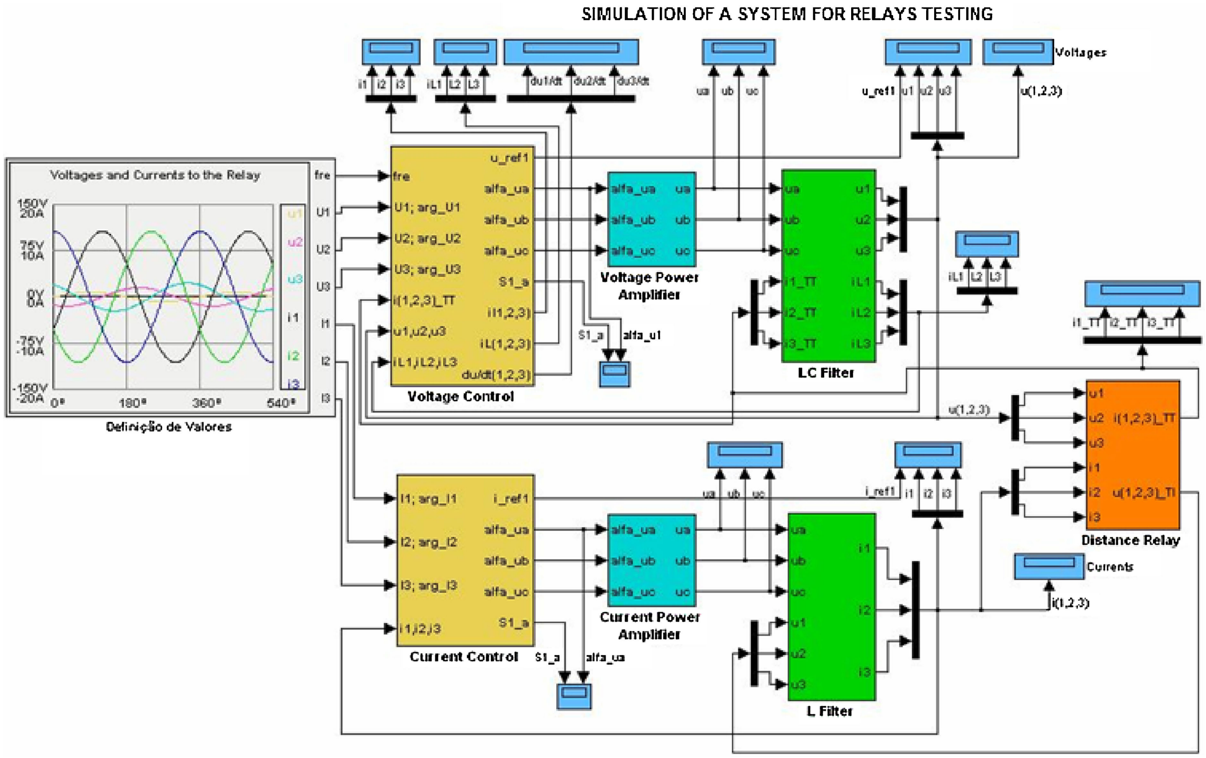

Figure 2 Matlab/Simulink system simulation. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

power network, and at the same time to be connected to a real relay. Hence, in this way it is possible to make a simulation of a fault and to see the operating action of a real relay. This allows the students to understand how the simulation tools are very near to a real power system.

The software tool was also developed in order to accept COMTRADE files [27]. This file type is used by digital relay systems to capture, store, retrieve, and analyze a fault record with very little effort. Hence, in this way the students can simulate the exact power system conditions that were originally recorded.

RELAY TYPES

A protection system usually includes three basic components:

- The transducers, which detect system abnormalities.
- The relays that provide signals to activate the protection device.
- The circuit breakers, the device that disconnects the circuit.

The oldest type of relays is the electromechanical type. It means that the principle of operation is related with currents acting with electromagnetic fields operating on mechanical devices, to establish the cut-off circuit operation order.

In a second technology evolution stage, this type of relays was replaced by solid-state relays, in which the electromagnetic analysis and the mechanical devices operation are made by electronic analog circuits. The electronic circuit reflects the electromagnetic interaction, in a fault situation.

Nowadays, computer-based relays (digital relays) using algorithm, which reflects the electromagnetic phenomena related to system abnormalities on power system networks, are largely used.

With the introduction of microprocessors it became possible to extend the protection to several functions such as, for instance, fault detection and classification. The protection systems became more accurate and faster in operation.

In our laboratory, we use the following relays:

- *Electromechanical type*: Brown Bovery (BBC)—TYP LH1w, TYP S A771191 P1, TYP LI 41a, TYP ISM 21, and TYP ISM21.
- *Solid-state type*: ABB STROMBERG—SPAJ 3C5 J3 and SPAJ 1F1 J3.

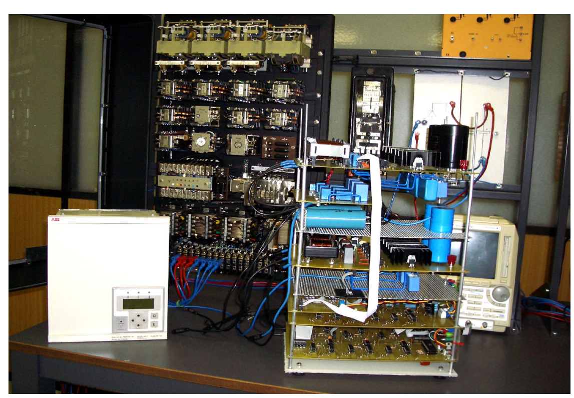

Figure 3 Experimental prototype set-up. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

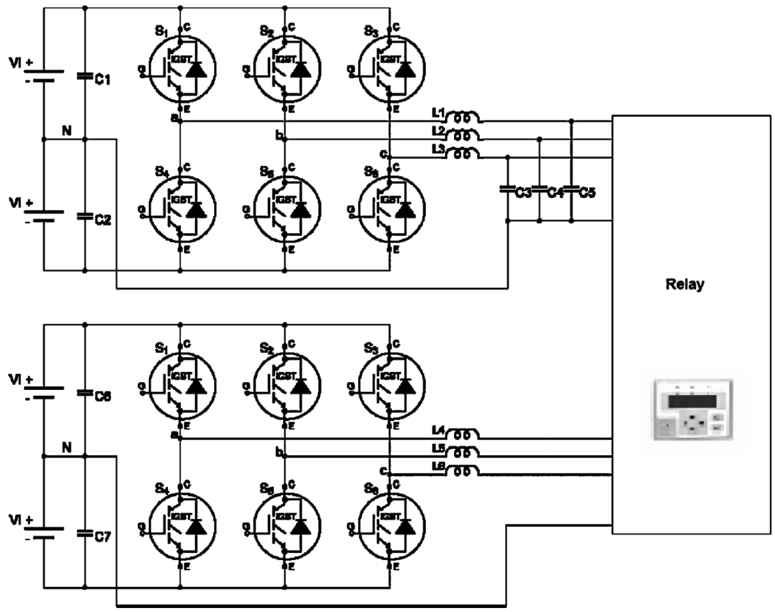

Figure 4 Schematic of the power amplifiers.

- *Computer-based type*: ABB—SPAJ 140 C, SPAA 121 C, SPAU 130 C, REL 511; Siemens 7SA5222 and Efacec TPU S420.

It became of great importance to our students to study the different types of relays. In fact, in our opinion the student acquires a greater sensibility to compute programs for digital relays if they are well informed about the principles of operation of the previous types of relays.

TESTING SYSTEM

A laboratory prototype of the power amplifier system for testing several relays operating characteristic was developed. Figure 3 shows the prototype used in the experimental set-up.

In the computer there is a digital simulator of different fault types. The digital simulator was developed in Matlab/Simulink and generates the test signals for a microcontroller that converts current and voltage references of the power converter amplifiers. In this laboratory prototype, an AT89S51 microcontroller from ATMEL was used. There are two power converter amplifiers. For both, the classical four-wire three-phase voltage source inverter topology was used. Figure 4 shows the schematic of the power amplifiers. One of the amplifiers generates voltages for the relay. In this way, there is a low-pass filter at the inverter output. The other generates currents for the relay. Hence, at the inverter output it is only necessary to use inductors in order to control and limit the relay currents. For both power converter amplifiers HGTG12N60A4D IGBTs was used. Figure 5 shows one of the power amplifiers prototype developed by the students, which generate the currents for the relays.

This laboratory prototype was developed in order to test electromechanical protections. In this way students can verify the limitations of this equipment. Another important feature is that it gives the students the real feeling of the protection operation. In fact, it is not a simple led which signals the protection operation but it is the mechanical noise of the operation itself. Therefore, in a practical way, students are allowed to feel the protection tripping. This system also allows a steady-state and dynamic testing of the relays.

LABORATORY EXPERIMENTS

This equipment is used to do several laboratory experiments such as the following performed in our school:

- *Experiment 1*: Testing an overcurrent and time delay.
- *Experiment 2*: Testing a directional protection.
- *Experiment 3*: Testing a distance protection.
- *Experiment 4*: Case study for the protection of a line interconnecting embedded generation.

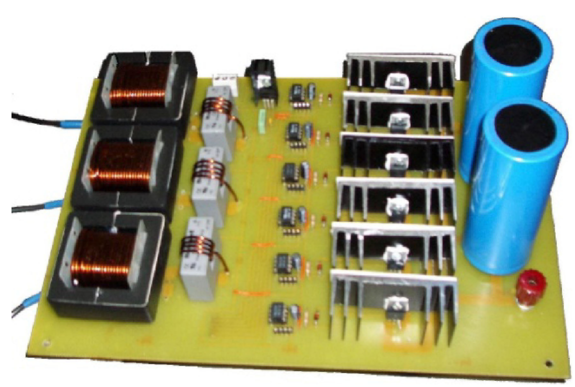

Figure 5 Prototype of the power amplifier that generates the relays currents. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

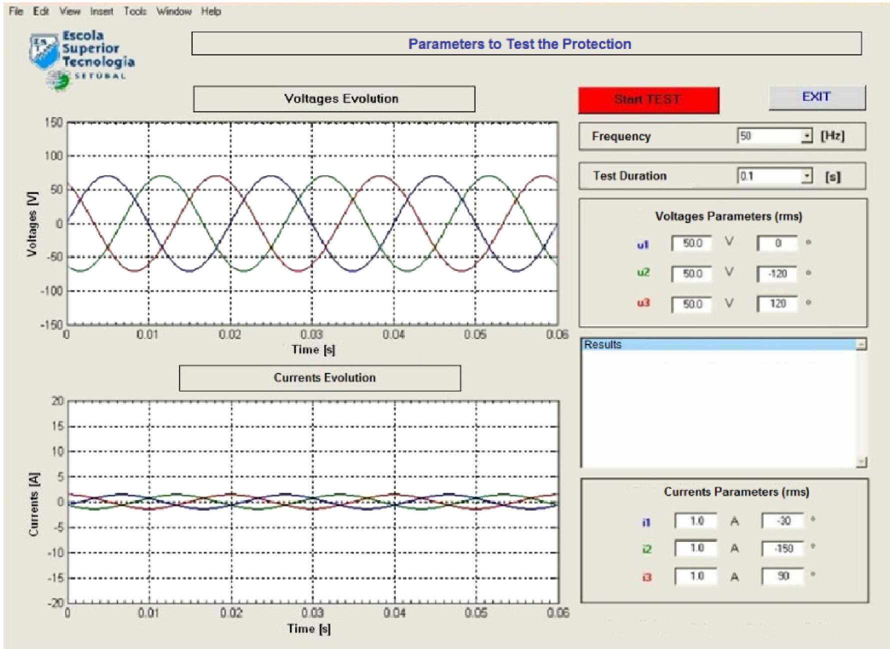

Figure 6 Screen of the obtained experimental result of the parameters introduced into the test system. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

In experiment 1, students do several tasks. They start to program the relays—the ABB SPAJ 140C and Stromberg 3C5 J3 are used. Then using the test equipment they can define the voltages and currents that are injected to the relays. In this way they can verify if the relay trip signal is at the expected parameters and the evolution of the voltages and currents. Figure 6 shows an example of the voltages and currents plotted values by the developed software.

This system also allows simulating several short circuits such as phase-to-phase or phase-to-earth faults. In this case students must choose the fault type and introduce the source and line parameters. Figure 7 shows one of the experimental results

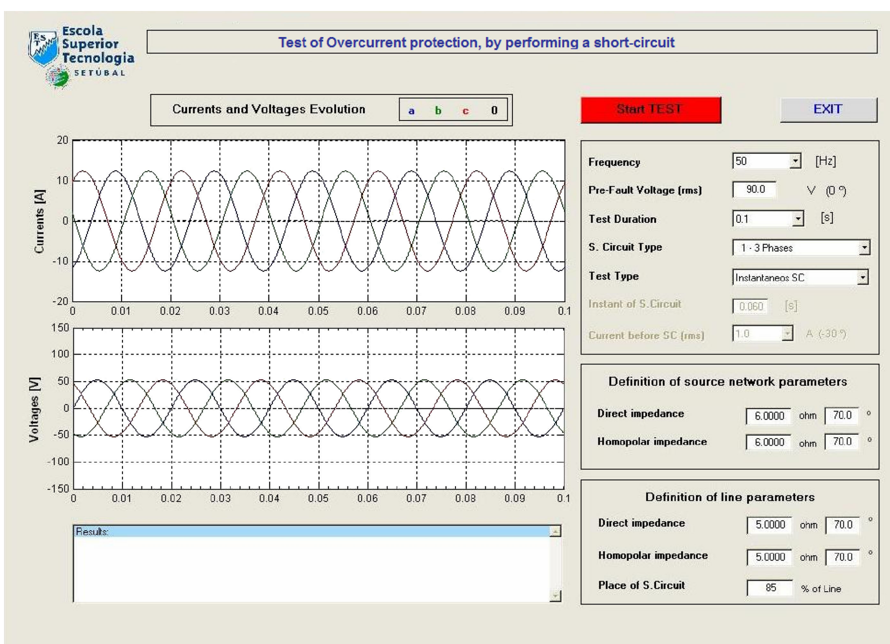

Figure 7 Screen of the obtained experimental result for the three-phase fault. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

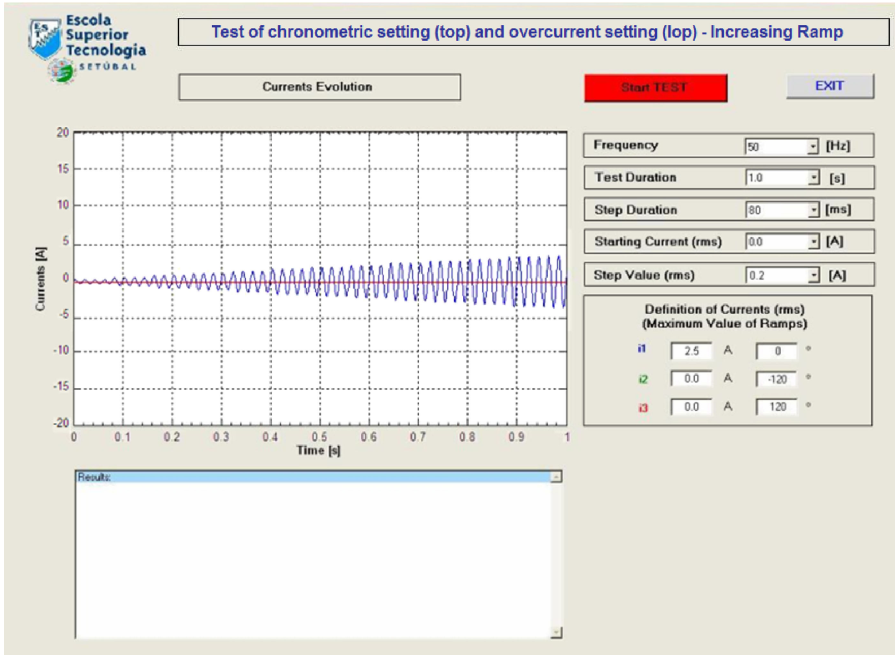

Figure 8 Screen of the obtained experimental result for the variation of the current amplitude. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

obtained. In this test, a three-phase fault is chosen, and the short circuit is located at 80% of the total line length in order to test zone 1 of distance protection.

They also must confirm the protection settings (current amplitude and delay of the tripping signal) to perform a test with a crescent variation of the current amplitude. For this, the students must define the testing time and current amplitude values. Figure 8 shows the experimental result of one of these tests. In this case the type fault is a phase-to-earth fault. They injected 2.5 A with crescent variation, during 1.0 s.

To verify the time protection settings, this system is also prepared to receive the tripping signal from the relay. In this way, the testing system gives information about the instant in which the relay was operated, allowing the students to verify if that operation is according to the expected results.

For experiment 2 the ABB STROMBERG 1F1 J3 and the EFACE TPU S420 relays were used. In this case directional relays require two inputs, the operating current and a reference, or polarizing, quantity (either voltage or current) that does not change with fault location. The students start to insert the protection settings. Then other students use the test system to verify if the protection settings are correct. The idea is to create a competition environment between students.

In experiment 3, the BBC LH1w and the ABB REL 511 relays were used for the distance protection tests. To perform these, students must choose the type of test: fault impedance. Figure 9 shows one of the experimental results obtained. It was chosen a phase-to-earth fault and the distance till the shortcut is 80% of the total line length in order to test the zone 1 of the distance protection.

This protection was previously calibrated with standard values according to the defined impedance values to the plotting of the mho curve. Students obtained the theoretical parameters to inject in the protection. In this test, the BBC LH1w device was used.

Figure 10 shows another experimental result. It shows another option of the developed system. Instead of the mho characteristics, the current and voltage time evaluation and the corresponding vector diagrams are presented.

Nevertheless, the vector graphics demonstrate several changes, which are related to the different instantaneous voltage and current curves.

To obtain the relay-operating characteristics, several anomaly tests were performed such as: overload or unbalanced loads, phase-to-earth fault, phase-to-phase-earth fault, phase-to-phase fault, and three-phase short circuit. In each one, the implemented tests look forward to locate the distance where the fault occurred.

In experiment 4 the tests are typically made for lines interconnecting embedded generation. In fact, with the great impact in embedded generation systems of windmill generators, it became more and more important to evaluate those types of faults. In this experiment several fault types such as the over- and undervoltage faults can be tested.

Figure 11 shows the experimental results testing a digital over voltage protection relay. A 6% overvoltage on the relay type ABB SPAU 130 C was injected. In this case there is a crescent variation of the voltage from 65 V (r.m.s.) to 72 V (r.m.s.), during 10 s.

With this application, the important frequency variation test can be done. Students program the relays for over- and underfrequency. By having a function of a crescent variation of the voltage and frequency, this system is able to verify the protection settings.

In this way, analyzing each frequency the tripping signal is activated and students can verify if the relay is working as expected.

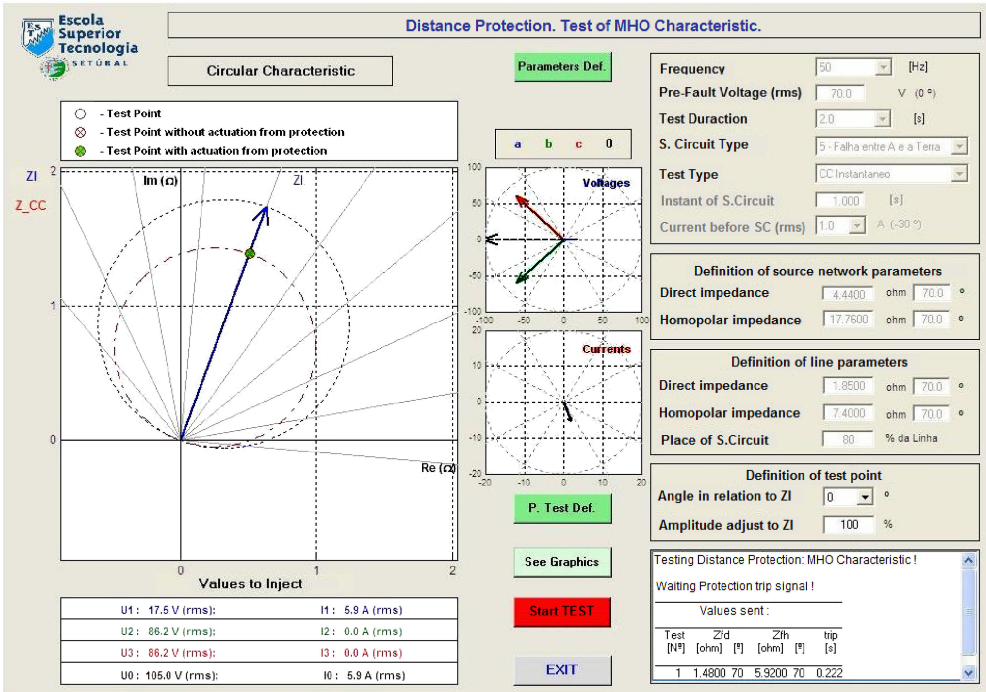

Figure 9 Screen of the obtained experimental result for the distance protection test of mho characteristic. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

As referred before, testing digital relays using COMTRADE is another option of the developed system. There are several COMTRADE files in the software tool that the students can have access (Fig. 12, in which the results are obtained from the local Electrical Company). Using these files, students do the following experiments:

- First they program a digital relay for a real power system network. Then they verify if there is a tripping signal or not.
- Four new COMTRADE files are inserted. In one or two of the files there will a small perturbation. In this situation, the relay must not activate a tripping signal. Hence, after students check that the relay does not activate the tripping

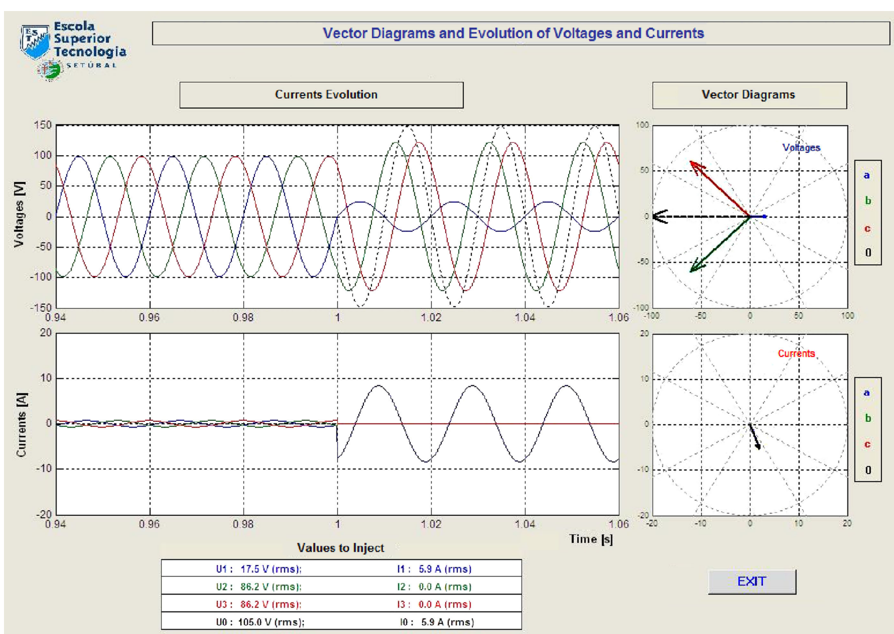

Figure 10 Screen of the obtained experimental result for the distance protection test of current and voltage evaluation. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

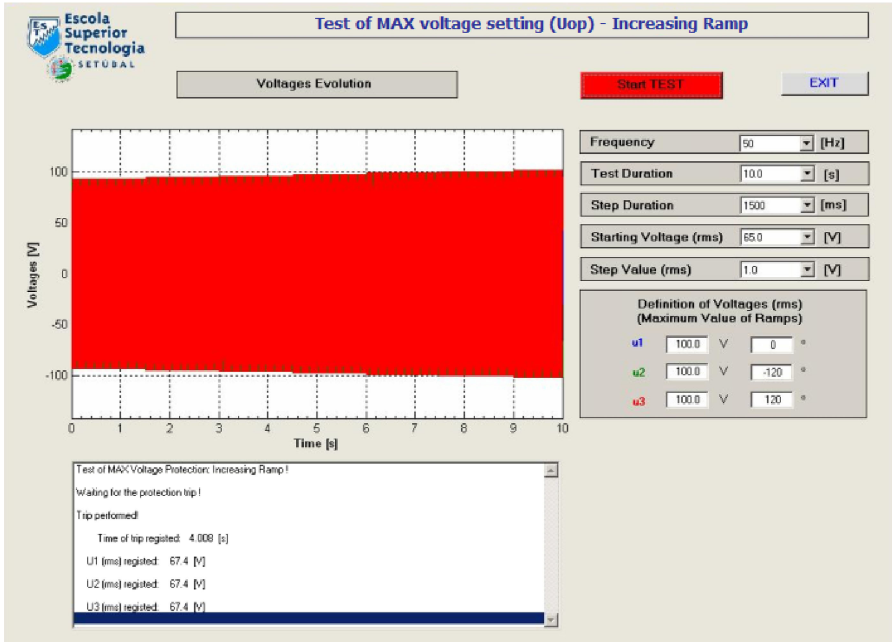

Figure 11 Digital overvoltage protection results. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

signal, they must download the file. Then they must verify if the non-activation of the tripping signal by the relay is correct.

The student response was very positive. A better understanding and an increased interest in power system protection was also another advantage of the introduction of this tool.

CONCLUSIONS

Teaching the subject of protection systems and all the underlying tests and experiments necessary for proper learning is really difficult. Many times, students do not have the ability to connect the digital tests performed in laboratory with computers in the real machinery that constitutes the protection devices. With this

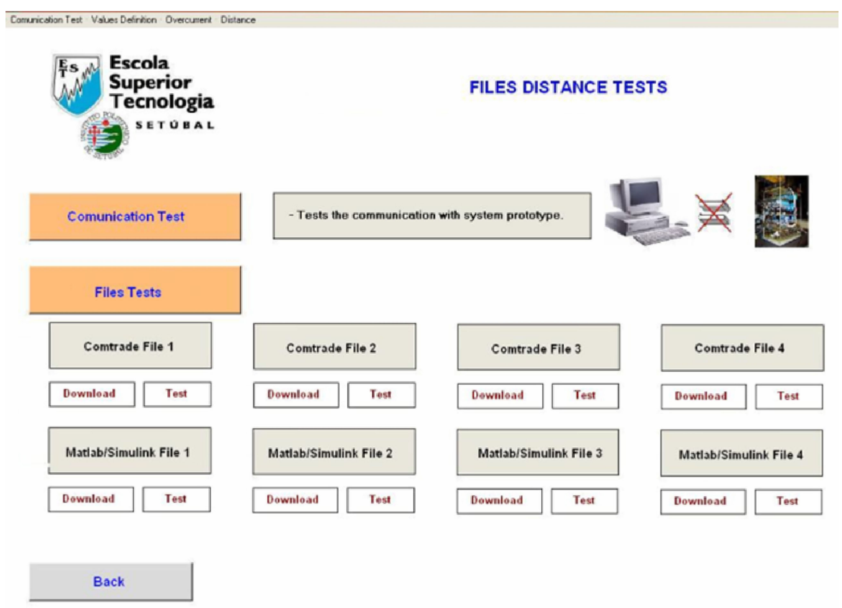

Figure 12 Option for the COMTRADE files. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

new system our main goal is to bring motivation to the students and give them the capacity to, by competing with other colleagues, perform their own real-based tests with mutual evaluation and verification of the results by both the teacher and the other students.

This new testing system consists of computer equipment, controller I/O interface, and power amplifiers, which are based on 2 three-phase inverters with a neutral wire. The simulator inside the computer equipment was developed in Matlab/Simulink allowing testing and evaluation of the relay-operating characteristic. The program communicates with a microcontroller in a bi-directional way, which allows sending the information for the power amplifiers and, at the same time, to receive information from the protection relay.

Using the proposed tool it is possible for the students to understand the performance and limitations of different protective relay systems. Finally, this tool also has flexible structure and a good graphical interface that enables users to choose different relay characteristics under different operating conditions.

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BIOGRAPHIES

L. Sousa Martins graduated in Electrical Engineering from the Instituto Superior Técnico (IST), Technical University of Lisbon, Lisbon, Portugal, in 1975 and received the MSc and PhD degrees in Electrical and Computer Engineering from Technical University of Lisbon, Portugal, in 1989 and 2003, respectively. His employment experience included the Siderurgia Nacional, Portugal, and SN-Angola/Voest Alpine, Angola. He is an associate professor at the Department of Electrical Engineering, Escola Superior de Tecnologia de Setúbal (ESTS), Instituto Politécnico de Setúbal, Portugal, since 1991. His primary areas of interest are in electric power networks, design and protection, electrical installations. His present research interests are in the areas of advanced power systems protections.

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V. Fernão Pires received the BS degree in Electrical Engineering from Institute Superior of Engineering of Lisbon, Portugal, in 1988, and the MS and PhD degrees in Electrical and Computer Engineering from Technical University of Lisbon, Portugal, in 1995 and 2000, respectively. Since 1991 he is a member of the teaching staff at Electrical Engineering Department of Superior Technical School of Setúbal – Polytechnic Institute of Setúbal. Presently, he is a professor teaching Power Electronics and Control of Power Converters. He is also a researcher with the Center for Innovation in Electrical and Energy Engineering, Technical University of Lisbon. His current research interests include the areas of control, modeling, and simulation of electrical systems.